European Commission

Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1

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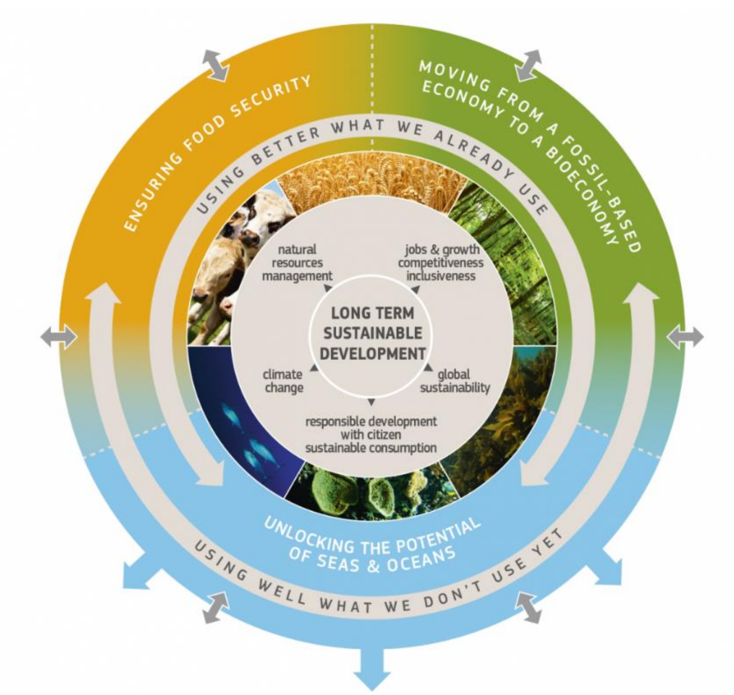

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Abstract

The present document compiles the main outputs of the environmental sustainability assessment in the framework of the Bioeconomy Observatory as at the end of 2014. The selection includes fourteen environmental sustainability factsheets and a brief explanatory document that provides an overview of the structure and content of the factsheets.
This report is the result of exchange and consultation with external experts on the technical content of bio-based factsheets.

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NOTE TO THE READER

In order to cope with an increasing global population, rapid depletion of many resources, increasing environmental pressures and climate change, Europe needs to radically change its approach to production, consumption, processing, storage, recycling and disposal of biological resources. Over the last decades, many policies have been put in place or revised by the EU to tackle these challenges and drive the transformation of the European economy. However, the complex inter-dependencies that exist between challenges can lead to trade-offs, such as the controversy about competing uses of biomass. The latter arose from concerns about the potential impact on food security of the growing demand for renewable biological resources driven by other sectors, the use of scarce natural resources, and the environment in Europe and third countries. Addressing such multi-dimensional issues requires a strategic and comprehensive approach involving different policies. Well-informed interaction is needed to promote consistency between policies, reduce duplication and improve the speed and spread of innovation[1].

The bioeconomy provides a useful basis for such an approach, as it encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy. Its sectors and industries have strong innovation potential due to their use of a wide range of sciences, enabling and industrial technologies, along with local and tacit knowledge.

The Bioeconomy Strategy and its Action Plan[2] aim to pave the way to a more innovative, resource-efficient and competitive society that reconciles food security with the sustainable use of renewable resources for industrial purposes, while ensuring environmental protection.

Amongst other activities, the Action Plan foresees the establishment, in close collaboration with existing information systems, of a Bioeconomy Observatory that allows the Commission to regularly assess the progress and impact of the bioeconomy, and to develop forward-looking modelling tools.

In February 2013, the setting up of a Bioeconomy Observatory was entrusted to the Joint Research Centre of the European Commission under an intra-institutional agreement (Administrative Arrangement Ref. 341300 – Bioeconomy Information System and Observatory, BISO).

Amongst other tasks in the framework of the Bioeconomy Observatory, the JRC is performing a comprehensive, independent and evidence-based environmental sustainability assessment of various bio-based products and their supply chains.

The present document compiles the main outputs of this environmental sustainability assessment as at the end of 2014. The selection includes the following documents:

- ✓ A **brief explanatory document** that provides an overview of the structure and content of the product and process environmental factsheets is included. This document summarises the **comprehensive, science-based methodology to assess the environmental sustainability of bio-based products and their supply chains, using a life-cycle perspective**[3]. This methodology is largely based on the Product Environmental Footprint (PEF) method developed by the JRC[4] and on previous research

[1] Adapted from COM(2012) 60 final, 13.2.2012
[2] COM(2012) 60 final, 13.2.2012
[3] Led by Simone Manfredi, simone.manfredi@jrc.ec.europa.eu
[4] The 2013 Recommendation of the European Commission "on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations" (2013/179/EU) supports the use of the PEF method when undertaking environmental footprint studies of products.

proposals of the JRC[5]. It provides a quantitative understanding of a wide range of environmental aspects, and facilitates the assessment of 14 default impact category indicators, including human toxicity, land use and resource depletion. The application of the methodology may help identify those parts of the production system that are most environmentally relevant. Hence, it represents a powerful tool to design actions to reduce the estimated environmental impacts. The methodology can also help to identify gaps in data and/or information availability or accessibility, as well as to focus data collection on those parameters or parts of the production system that most influence its environmental performance.

- ✓ **Fourteen environmental sustainability factsheets**. These are divided into three groups that reflect the three "pillars of bioeconomy": (1) food & feed, (2) bio-based products and (3) bioenergy, including biofuels. The factsheets give a uniform summary of different bioeconomy value chains and provide information on their environmental performance, based on publicly available data and/or information. The fourteen environmental factsheets are:
  - Food and feed[6]: Eggs, Milk, Wheat, Wine;
  - Bio-based products[7]: 1,3-Propanediol, Glycerol, Lactic Acid, Polylactic Acid, Polyhydroxyalkanoates, Acetic Acid, Succinic Acid, Adipic Acid;
  - Bioenergy, including biofuels[8]: Bioalcohols via Fermentation, Biodiesel via Transesterification.

In line with the Terms of Reference of the intra-institutional Administrative Arrangement 341300, the environmental sustainability research activities performed in the framework of the Bioeconomy Observatory are built on existing *and* accessible instruments (data, information and analyses) developed by EU, national and international organisations, and on the results of relevant EU-funded projects. The factsheets also contain a knowledge gap analysis, to highlight where data and/or information either do not exist or are inaccessible. These gaps, in turn, indicate the need for further action at policy level, in order to produce a comprehensive and evidence-based snapshot of the European bioeconomy.

In the period until the end of the intra-institutional Administrative Arrangement, the environmental sustainability assessment of bio-based products and their supply chains will comprise of the following activities:

- ✓ Continuous mapping and collection of data and information from various sources, complemented by critical review, analysis, assessment and calibration, leading to the production of additional environmental factsheets**;**
- ✓ Comparative life-cycle assessment of a selection of bio-products and supply chains;
- ✓ Intensive interactions and exchange with stakeholders – a third stakeholders' consultation workshop[9] on the environmental sustainability assessment of bioeconomy value chains is planned for October 2015.

The JRC also intends to initiate broader modelling activities (e.g. to assess the competing uses of biomass and land in a multi-sector approach) and to develop display tools that will facilitate the presentation of the results from the environmental sustainability assessment.

B. Kavalov

[5] Bioeconomy and sustainability: a potential contribution to the Bioeconomy Observatory, V. Nita, L. Benini, C. Ciupagea, B. Kavalov, N. Pelletier, EUR 25743 EN – 2013

[6] Led by Jean-Philippe Aurambout, jean-philippe.aurambout@jrc.ec.europa.eu;

[7] Led by Cristina Torres de Matos, cristina.matos@jrc.ec.europa.eu;

[8] Led by Jorge Cristobal Garcia, jorge.cristobal-garcia@jrc.ec.europa.eu;

[9] The first two workshops, co-organised with Imperial College – London (UK), took place in October 2013 and November 2014.

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EXPLANATORY DOCUMENT

INTRODUCTION

This document provides an overview of the structure and content of the product and process environmental factsheets available on the Bioeconomy Observatory web pages. These factsheets are divided into three groups that reflect the three pillars of the bioeconomy: (1) **food & feed**, (2) **industrial bioproducts** and (3) **bioenergy.** Compiled based on publicly available data/information collected from studies using life cycle assessment (LCA), they describe different bioeconomy value chains and their environmental performance.

The following describes each of the three sections of the environmental factsheets.

Section 1: PROCESS/PRODUCT INFORMATION

Objective & content

This first section describes the different processes and products involved in the various bioeconomy value chains, taking into account their uses and production flows. It includes:

- A **flow-sheet** that depicts the main steps in the process, from the input used (i.e. type of biomass) to the final product(s), considering the most significant intermediate products and co-products.
- A **technological overview** that provides information on the state-of-the-art technologies and process configurations of the particular bioeconomy value chain. It particularly emphasises the input used.
- The **technology readiness levels** (TRL), which describe the maturity of the technologies and configurations used. TRL 1-3 is used to indicate basic and applied R&D, TRL 4-5 the pilot test stage, TRL 6-7 the demonstration stages and TRL 8-9 the commercial stages. An uncertainty range is provided given that an industrial technology can take 3-5 years to progress to the next TRL level.
- A **SWOT analysis** of the Strengths, Weaknesses, and Opportunities and Threats of the process/product.

Section 2: ENVIRONMENTAL DATA AND INFORMATION

Objective & content

This section maps and presents the available relevant environmental aspects and information regarding the different bioeconomy value chains, and provides an overview of their environmental performance calculated using a life cycle approach. In addition, it aims to:

- Identify knowledge gaps or information availability/accessibility issues that could be addressed by further research.
- Identify and explain the differences and similarities of LCA methodologies and results with regard to the bioeconomy value chains.

The environmental data and information section includes:

- The **system boundaries of the environmental assessment**, which depict and explain the LCA boundaries (see definitions below) considered.
- The **settings and impacts of the environmental assessment**. This is the main section of the environmental factsheet. It reports data collected from the scientific literature in a table that groups LCA results for the different impact categories (focusing on those considered in Table 1) by studies which use the same input to produce the same product within (as far as possible) comparable system boundaries. Maximum and the minimum values are displayed for the same functional unit. This grouped data can, however, include results obtained using different allocation methods (see definitions below) and different geographical coverage, which may bias the robustness of the ranges provided.
- **Comments and interpretation of the environmental performance**, which includes explanations of the LCA results and a graph that depicts all data after normalisation (i.e. not just the maximum and minimum) for the most reported impact categories. This graph allows the reader to:
    1. Further analyse the data mapped;
    2. Compare results across the different impact categories (as all impacts have been normalised and are therefore expressed in the same unit);
    3. Identify the effect of inputs or some key LCA assumptions on the final results.

Table 1. Impact categories provided in the Environmental Sustainability Assessment methodology developed within the Bioeconomy Information System Observatory (BISO) project. This methodology is based on the Product Environmental Footprint, as recommended by the European Commission [3].

Impact Category	**Impact Assessment Model**	**Normalisation Factor for EU / Impact Category indicators**
Climate Change	Bern model - Global Warming Potentials over a 100-year time horizon.	$4.60E^{12}$/ kg CO_2 eq.
Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization over an infinite time horizon.	$1.08E^{7}$/ kg CFC-11 eq.
Ecotoxicity for aquatic fresh water	USEtox model	$4.36E^{12}$ / CTUe*
Human Toxicity - cancer eff.	USEtox model	$1.84E^{4}$/ CTUh**
Human Toxicity – non-cancer eff.	USEtox model	$2.66E^{5}$/ CTUh**
Particulate Matter/Respiratory Inorganics	RiskPoll model	$1.90E^{9}$/ kg $PM_{2.5}$-eq.
Ionising Radiation – human health effects	Human Health effect model	**$5.64E^{11}$/ kg U^{235} eq. (to air)**
Photochemical Ozone Formation	LOTOS-EUROS model	$1.58E^{10}$/ kg NMVOC eq.
Acidification	Accumulated Exceedance model	$2.36E^{10}$/ mol H+ eq.
Eutrophication – terrestrial	Accumulated Exceedance model	$8.76E^{10}$/ mol N eq.
Eutrophication – aquatic	EUTREND model	$7.41E^{8}$/ fresh water: kg P-eq. $8.44E^{9}$/ marine: kg N-eq.
Resource Depletion – water	Swiss Ecoscarcity model	$4.06E^{10}$/ m^3 water used
Resource Depletion – mineral, fossil	CML2002 model	$5.03E^{7}$/ kg Sb-eq.
Land Transformation	Soil Organic Matter (SOM) model	$3.74E^{13}$/ Kg (deficit)

* Comparative Toxic Unit for ecosystems
** Comparative Toxic Unit for humans

Section 3: REFERENCES / FURTHER INFORMATION

Objective & content

This section gives the references used in the environmental factsheets, and tables further references to the main FP7 projects related to the environmental sustainability assessment of the specific target process / product. More information on these projects can be found in the Community Research and Development Information Service - CORDIS (http://cordis.europa.eu/home_en.html).

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Definitions and clarification of key LCA concepts

Life Cycle Assessment (LCA) [1] – the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (where life cycle means from the extraction of resources to the use of the product and its management after it is discarded – "from the cradle to the grave").
Functional unit – a measure of the function of the studied system. The functional unit provides a reference against which the inputs and outputs can be related. It identifies the function provided, in which quantity, for what duration and to what quality [2].
System boundaries – determine which processes are included in the LCA study. They can be the boundaries between technological systems and nature, geographical areas, time horizons and different technical systems. The main variants (Fig. 1) are: Cradle-to-Grave, Cradle-to-Gate and Gate-to-Gate. The Well-to-Wheel (WTW) is a special approach for biofuels that includes fuel production (Well-to-Tank) and vehicle use (Tank-to-Wheel). The WTW boundary variant usually focuses only on greenhouse gas emissions and energy efficiency and, unlike typical LCA boundaries, does not consider the building phase of facilities/vehicles nor end-of-life aspects.

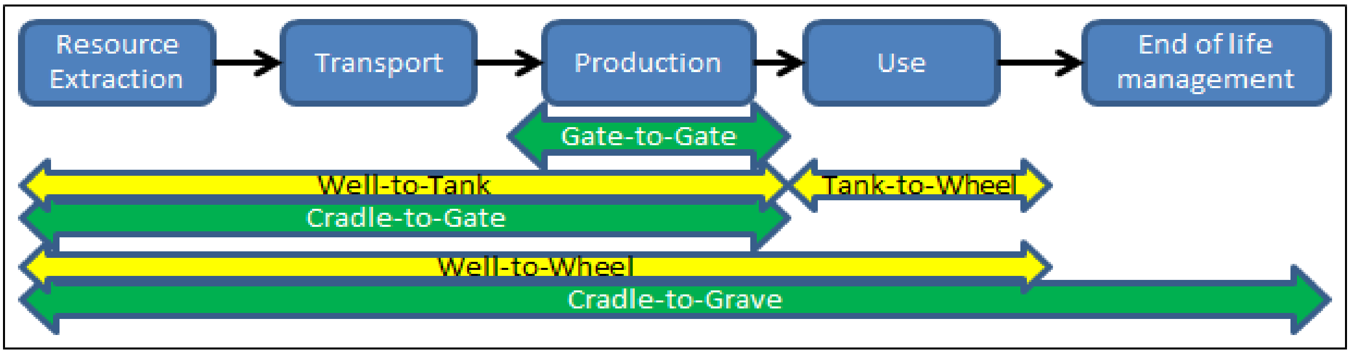


Figure 1. Main variants of life cycle assessment system boundaries

Impact Categories and Models define what classes of impacts are considered in the assessment; these are associated with specific impact assessment models that aggregate the inventory data and calculate the size of their contribution to each impact category using characterisation factors (i.e. values of the impact intensity of a substance relative to a common reference substance for a given impact category, e.g. CO_2 is the reference substance for the category "Climate Change").

Normalisation is an optional LCA step (under ISO 14044:2006) that follows the characterisation step. Through normalisation, the calculated environmental impacts are converted into the same (dimensionless) unit for all impact categories. This allows for the comparison of environmental impacts across different categories.

Multifunctionality – If a process or product provides more than one function, i.e. delivers several goods and/or services (often also called "co-products"), it is multifunctional [2]. There are several approaches that deal with multifunctionality. Based on the ISO 14044:2006 guidelines, the latest multifunctionality decision hierarchy supported by the European Commission (as from the 2013 EC Product Environmental Footprint guide) reads:

1. *Subdivision or System expansion* – Wherever possible, subdivision or system expansion should be used to avoid allocation (see point 2 below). Subdivision disaggregates multifunctional processes or facilities to isolate the input flows that are directly associated with each product output. System expansion expands the system by including additional functions related to the co-products.
2. *Allocation* – refers to how the individual inputs and outputs are split between the co-functions according to some allocation criteria.
    - **Allocation based on an underlying physical relationship** - When choosing allocation criteria, preference should be given to a physical relationship (i.e. the element's content, mass, etc.). Alternatively, allocation based on an underlying physical relationship can also be modelled via **direct substitution** whenever the actual product substituting the bio-based product is known.
    - Alternatively, **allocation based on different relationships** can be used, such as economic allocation, whereby inputs and outputs associated with multi-functional processes are allocated to the co-product outputs based on their relative market values. If the product that substitutes the bio-based product is not known, allocation based on different relationships can be modelled via **indirect substitution**, whereby the substituted product is represented by the market average.

Assumptions & limitations

The main limitation of this assessment process is the poor availability and/or accessibility of relevant data and information, which may limit the robustness of the environmental analysis (and, in particular, the representativeness of ranges of environmental impacts). The references/studies used for mapping the LCA results in the factsheets were selected based on the following criteria:

- Studies from Framework Programme 7 (FP7). Generally the publicly available LCA data from FP7 projects is limited and aggregated (e.g. reported as comparison percentages) which prevented their use in the environmental factsheets.
- Studies that reported environmental impacts that were calculated in line with the Product Environmental Footprint methodology recommended by the EC [3] (shown in Table 1).
- Studies that focused on a broad range of environmental aspects, i.e. priority was given to studies accounting for the highest number of impact categories.
- Peer-reviewed literature and most cited and most recent studies.
- Studies with obsolete, incomparable or dubious quality data were excluded.

Another limitation is the lack of heterogeneity of the LCA results reported, mainly due to the different assumptions and different methodological choices made in the various LCA modelling exercises. As a consequence, several studies were not used to compile the factsheets, since their inherent differences made a comparison of the results meaningless. These differences mainly relate to:

- The different impact assessment methods used, as different methods may consider, for example, different substances for a given impact category, and different characterisation factors for the same substance.
- The definition of the system boundaries and the stages included in the study (e.g. even if the same general system boundaries are considered - e.g. cradle to gate - some studies may or may not include intermediate transport, construction and decommissioning of buildings, etc.).
- The definition of the functional unit (e.g. as the input, the output product, the agricultural land unit, etc.) [4]. The analysis performed to compile the environmental factsheets mitigates this variability since all the LCA data were converted to the same functional unit whenever possible.
- The consideration of direct and indirect land use change (dLUC and iLUC, respectively) [4].
- The definition of some impact categories (e.g. using different terminology or different units).
- The technology considered in the process and its maturity level.
- The approach used to mode the multifunctional system. For instance, if substitution is used, the reference system selected may have a significant influence on the final LCA results. On the other hand, if allocation is used, the selection of the allocation criteria and the relative contribution of each co-product may considerably influence the results of the assessment.

Normalisation was conducted whenever possible using normalisation factors that represent emissions from the EU-27 for the year 2010, based on the "domestic emissions inventory"[10] reported in the 2014 JRC Technical Report "Normalisation method and data for Environmental Footprints" (available online: https://ec.europa.eu/jrc/sites/default/files/lb-na-26842-en-n.pdf) [5].

The reported data were normalised using a common reference value (i.e. the total emissions in Europe within a certain impact category in the reference substance equivalents) to express all impact values using the same unit so that they can be compared across different impact categories. These impacts also represent the relative contributions of the system to the total environmental impacts caused by European domestic emissions. For example, with respect to climate change, if the system were estimated to have an impact value of 10 kg CO_2-eq., and if the normalisation factor for climate change in Europe were 1 000 kg CO_2-eq., then the normalised impact value for climate change would be 10/1 000 = 0.01, which means that the system assessed contributes 1% of the total impact on climate change associated with all domestic emissions in Europe.

For impact categories different from those listed in Table 1, normalisation factors for EU emissions were taken from the ReCiPe impact assessment method [6] and, for the primary energy category, the factor of 4.03×10^{13} MJ was used [7]. The ReCiPe method is a widely used LCIA (Life Cycle Impact Assessment) method that, like the Product Environmental Footprint method, transforms the emissions of the analysed value chains into impact scores[6,8].

References for this explanatory document

[1] UNE-EN ISO 14040:2006.
[2] EC – JRC – IES, 2010. ILCD Handbook – General guide for life cycle assessment – detailed guidance.
[3] EC, 2013. Recommendation (2013/179/EU).
[4] Cherubini & Stromman, 2011. Bioresource Technology, 102: 437 – 451.
[5] EC – JRC - IES, 2014. JRC Technical Report - Normalisation method and data for environmental footprints 2014.
[6] Sleeswijk et al., 2008. Science of the Total Environment, 390: 227 – 240.
[7] Rettenmaier et al., 2010. 4F CROPS: Future Crops for Food, Feed, Fiber and Fuel, Life cycle analyses (LCA) Final report on Tasks 4.2 & 4.3.
[8] http://www.lcia-recipe.net/home

[10] The "domestic emissions inventory" includes all emissions originating from activities taking place within the European Union territory.

Food & Feed Pillar

ENVIRONMENTAL FACTSHEET: ***Chicken Eggs***

PRODUCT INFORMATION

For the purpose of this exercise, eggs are defined as agricultural products produced by the females of birds (eggs from reptiles, fish and amphibians are not considered here), primarily from chickens and, to a lesser extent, quails and ducks in Europe. Chicken eggs consist of a protective shell, made of calcium carbonate, the albumen (or egg white), composed of 90% water and 10% proteins (mainly albumins), and the yolk, composed of 52% water, 26% fat (mainly oleic and palmitic acids), 16% proteins and 4% carbohydrates. The average hen produces 300 eggs per year, but this varies as a function of the hen's breed, diet and production environment.

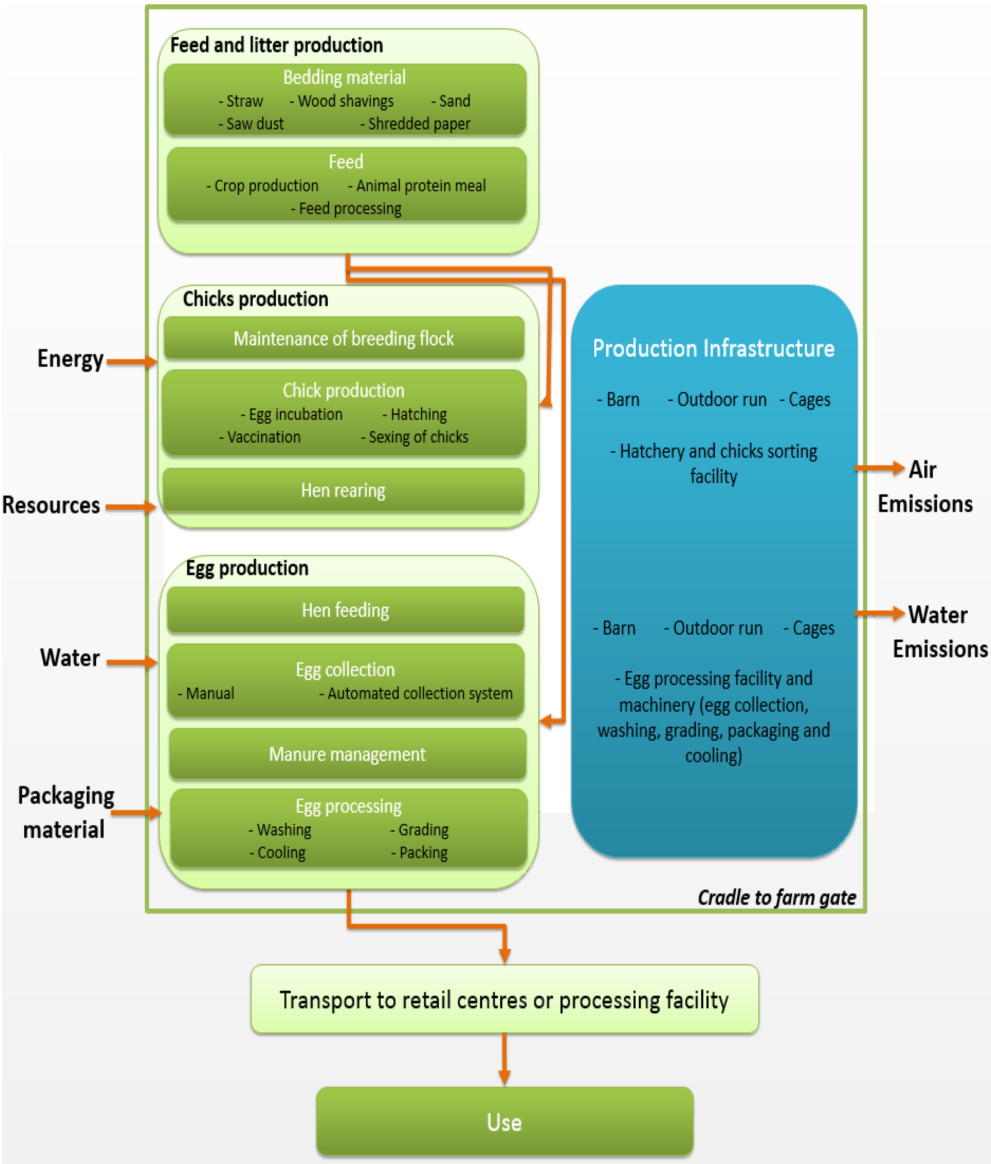


Figure 1: *egg production chain and system boundary*

EU production: 7.4 million tonnes [1] (2013).

Co-products: mature spent hens (mostly used for pet food), broken eggs, used litter and chicken manure. The processes involved in egg production are detailed in Fig. 1.

Egg production systems can be classified in four groups:

- *Caged (battery):* where chickens are kept exclusively in cages in covered enclosures.
- *Deep litter:* where chickens are kept in covered enclosures but can move freely.
- *Free range:* where chickens are kept in covered enclosures, can move freely and have access to open air areas.
- *Organic:* where chickens are kept in free-range conditions but are fed exclusively organic feed and are not administered anti-biotics.

Caged, deep litter, free range and organic egg production systems are all in operation at full commercial scale. Since 2012, "traditional" hen cages have been banned in the EU and only "enriched cages", which provide better welfare for hens, are allowed. Egg production across all processes is highly industrialised, and processes such as chicks breeding, feeding or egg collection are largely automated. Past research activities in the egg producing area have led to major increases in feed use efficiency and egg production per hen[2]. The technology readiness levels of different activities in egg production practices are presented in Figure 2. Current research and development activities for all egg production systems focus mainly on feed improvement (in particular feed digestibility), hen housing and welfare, and improving the quality of eggs. Research on organic production systems also focuses on the improvement and selection of chicken breeds as well as ways to better manage hen health and the occurrence of diseases.

Technology Readiness Levels

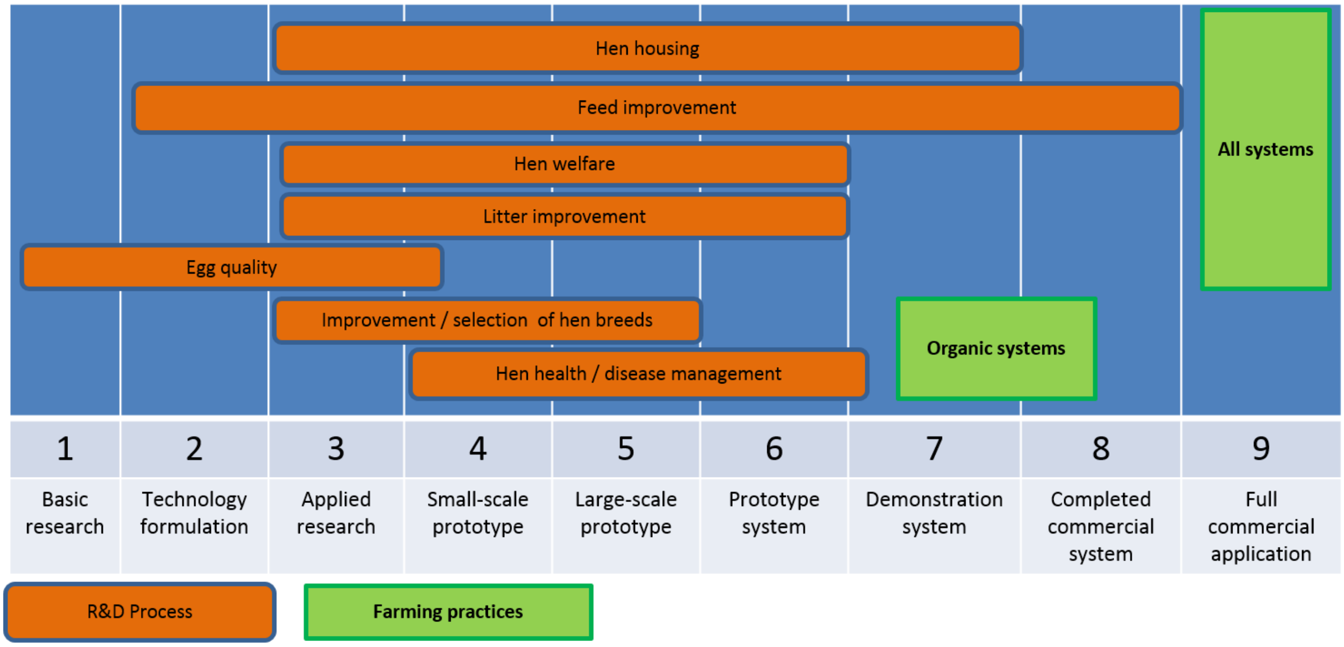


Figure 2: *Technology readiness levels for egg production systems.*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Eggs are produced worldwide, and a variety of chickens and production systems are available in most areas. **S2.** The egg production industry is very mature, the process of egg production is well understood, and most steps are automated.	**W1.** Organic production systems still suffer, more than other systems, from issues related to suboptimal diet, feather picking and cannibalism. **W2.** Certain industry practices may be negatively perceived by consumers with regard to hen welfare and the disposal of male chicks
O1. R&D in the area of food improvement has the potential to further increase feed use efficiency, making egg production even more competitive with other sources of animal protein. **O2.** The market for eggs is increasing, and includes the pharmaceutical industry.	**T1.** The egg production industry is mostly dependant on external feed and could be negatively affected by increases in feed prices. **T2.** The occurrence of diseases can have major impacts on egg production systems where hens are typically kept in high density.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

- Cradle to farm gate includes feed and litter production, the rearing of breeding flocks, the hatching of eggs, the rearing of egg-laying hens, as well as egg production and processing (collection, washing, grading and cooling).

Table 1 shows the environmental indicators associated with the production of eggs under (1) caged systems (pre-2012), (2) enriched caged systems, (3) deep litter systems, (4) free-range systems and (5) organic systems.

The most widely reported environmental impact categories are Climate change, Acidification, Eutrophication, Energy use and Land occupation (the use of fossil phosphorus, not presented here, is also reported in some studies). Few or no results were found for the remaining impact categories.

Environmental assessment: settings & impacts

Table 1: LCA indicators calculated for different egg production systems in the European Union. Functional unit in kg of egg. System boundaries: cradle to farm gate

Agricultural practices	**Caged (pre 2012)**	**Enriched Cages**	**Deep litter**	**Free range**	**Organic**
References	[3-7]	[8]	[3-5, 9]	[3-6, 10]	[4-6, 11, 12]
Geographical coverage	France, UK, the Netherlands	France	France, UK, the Netherlands	France, UK, the Netherlands	France, UK, the Netherlands
Impact categories from Environmental Sustainability Assessment methodology					
Climate change (kg CO_2-eq.)	1.67-5.25	1.74	2.33-4.6	2.13-6.18	1.42-7.0
Additional impact categories					
Acidification (kg SO_2-eq.)	$2.30E^{-2}$- 0.3	$3.9E^{-2}$	$4.0E^{-2}$ – $6.5E^{-2}$	$3.8E^{-2}$- 0.31	$3.30E^{-2}$- 0.34
Eutrophication – aquatic (kg PO_4-eq.)	$1.4E^{-2}$-$7.5E^{-2}$	$1.4E^{-2}$	$1.7E^{-2}$-$2.03E^{-2}$	1.60 E^{-2}-$8.0E^{-2}$	$1.7E^{-2}$-$1.02E^{-2}$
Energy use MJ/kg	13-20.7	N.A.	13.4-23.2	13.7-23.8	14-26.41
Land occupation (m^2)	2.82-6.3	2.91	3.42-5.7	3.56-7.8	4.9-16.9

N.A.: Not Available

The normalisation presented in Figure 3 was performed using the normalisation factors provided in the JRC 2014 methodology [13] and ReCiPe normalisation values (see explanatory factsheet).

Comments and interpretation of environmental performance (Table 1 & Figure 3)

- On a normalised scale for the EU-28, acidification is the greatest environmental impact associated with egg production, mainly because of ammonia emissions.
- The lowest impacts were found to be on land occupation, acidification and energy use as reported for caged systems, mainly because of higher densities and better feed conversion efficiencies. This system also had the second lowest impact on climate change. Organic systems had the highest environmental impact for all four categories (land occupation, acidification, energy use and climate change).
- Environmental impacts vary between worst and best performers by a multiplying factor of fifteen for acidification, six for land occupation, five for climate change and two for enery use. Significant differences exist within systems (particularly for organic egg production

systems), and can be explained mainly by differences in the type of hen housing and outdoor access, feed production and feed conversion.

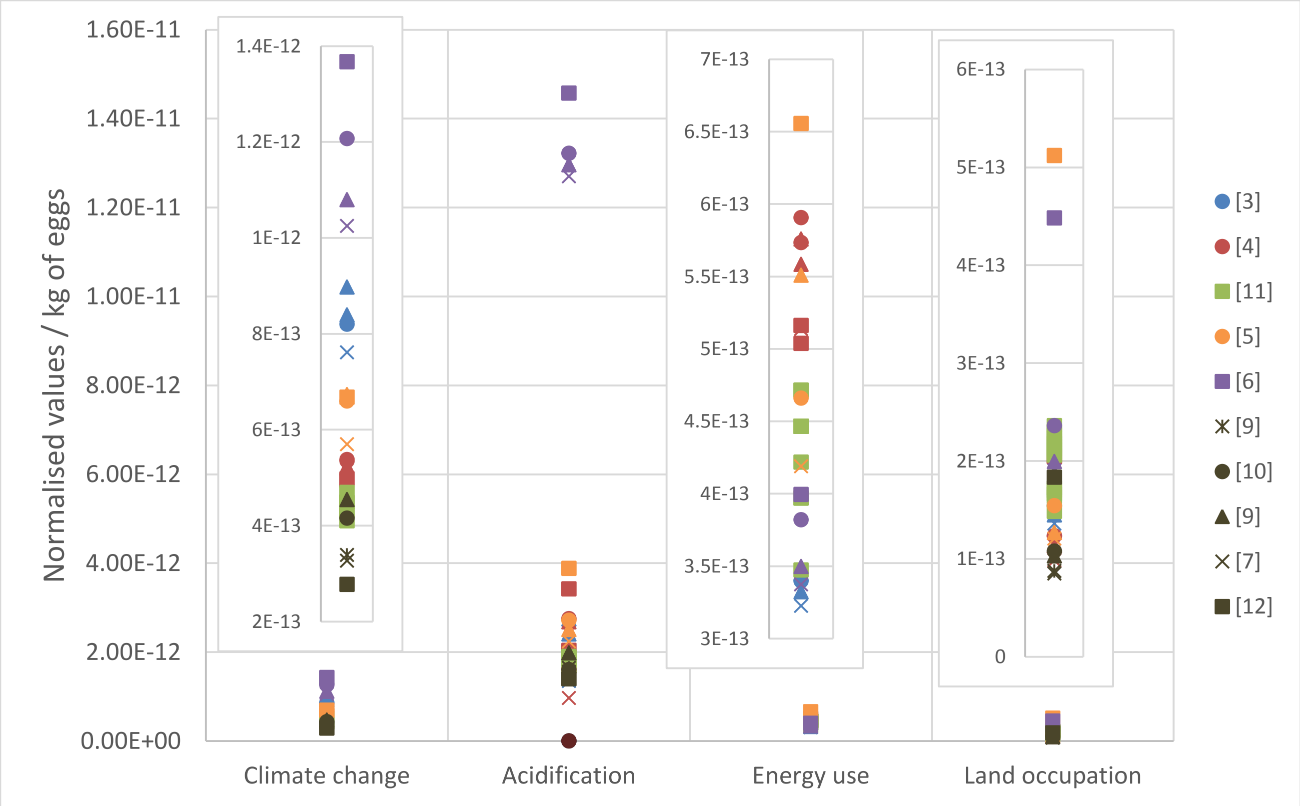


Figure 3: *Environmental performance expressed as normalised impact categories. Crosses correspond to conventional cages (pre 2012), stars correspond to post 2012 cages, triangles correspond to deep litter, circles correspond to free range, and squares correspond to organic systems.*

REFERENCES / FURTHER INFORMATION

[1] Prevision des experts, secteur des oeufs et de la viande de volailles [http://www.eepa.info/Download.aspx?dlqd=4828d96b-283a-4eee-8d5f-dcb376269221]

[2] Hongwei et al., 2013. A comparative assessment of the environmental footprint of the U.S. egg industry in 1960 and 2010, In.: Egg Industry Center; 28.

[3] de Vries and de Boer, 2010. *Livestock Science*, 128(1-3):1-11.

[4] Dekker et al., 2011. *Livestock Science*, 139(1-2):109-121.

[5] Leinonen et al., 2012. *Poultry Science*, 91(1):26-40.

[6] Williams et al, 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities, In: *Main Report Defra Research Project IS0205.* Bedford: Cranfield University and Defra.

[7] AGRIBALYSE, 2014. Oeuf, conventionnel, en batiment, en cage, In. ADEME.

[8] AGRIBALYSE, 2014. Oeuf, conventionnel, en batiment, en cage, reglementation 2012, In. ADEME.

[9] AGRIBALYSE, 2014. Oeuf, conventionnel, en batiment, In. ADEME.

[10] AGRIBALYSE, 2014. Oeuf, conventionnel, plein air, In. ADEME.

[11] Dekker et al., 2013. *Livestock Science*, 151(2-3):271-283.

[12] AGRIBALYSE, 2014. Oeuf, biologique, In. ADEME.

[13] JRC Report, 2014. Normalisation method and data for Environmental Footprints, In.: European Commission, Joint Research Centre; 92.

ENVIRONMENTAL FACTSHEET: ***Cow's Milk***

PRODUCT INFORMATION

Milk is a liquid agricultural product extracted from mammals (primarily from cows and to a lower extent buffalo, goat and sheep in Europe) as a result of dairy activities. Milk is a water-based emulsion of lipids (2.5-6%), carbohydrates (3.6-5.5%), proteins (2.9-5.0%) and minerals. The fat, sugar and protein content of milk varies significantly as a function of a cow's breed, age, diet and stage of lactation. Production per cow also varies between 6.8 and 17 tonnes per year, depending on the breed and management practices. Milk is the basis for a range of derived products, including butter, cheese, cream, whey, casein and milk powder.

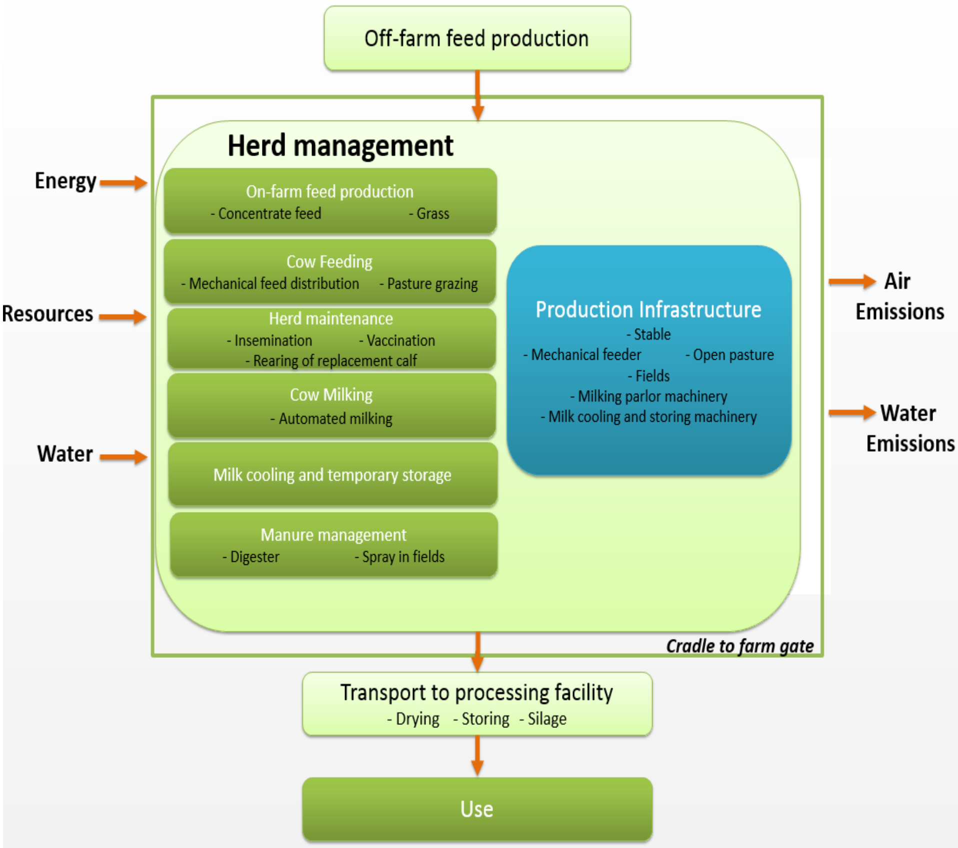


Figure 1: *milk production chain and system boundary*

EU production: 140 million tonnes (2012).

Co-products: meat (from veal and non-productive cows), urea and manure.

The processes involved in milk production are detailed in Figure 1.

Dairy enterprises vary in size and degree of intensification, ranging from:

- *Extensive production systems:* where cows are allowed to graze outdoors and fed mainly on grass.
- *Intensive production systems:* where cows are kept mostly indoors and fed a large proportion of concentrated feed (cereals, silage, etc.).

Organic dairy activities are often closer to extensive systems (which incorporate grazing) and require all feed to come from organic sources. They do not allow for the use of antibiotics or the application of chemical fertiliser to pastures.

Both intensive and extensive milk production systems are in operation at full commercial scale.

Technology readiness levels of different activities for both conventional and organic practices are presented in Figure 2. Intensive dairy systems have been the subject of intense research efforts in the past, and current research activities are mainly focused on improving feed for cows. The ultimate goal is to minimise costs and methane emissions while maintaining or increasing milk production. Extensive dairy production is highly dependent on pasture production, and most of its research activities focus on better pasture management – species composition, fertilisation regime and weed management.

The management of nutrients from cow manure is a problem for both intensive and extensive systems. Research activities in nutrient management, ranging from basic research to commercial systems, principally focus on nutrient use optimisation (from cows' diets to the application of manure to pastures) and on manure storage and treatment (i.e. slurry digesters).

Technology Readiness Levels

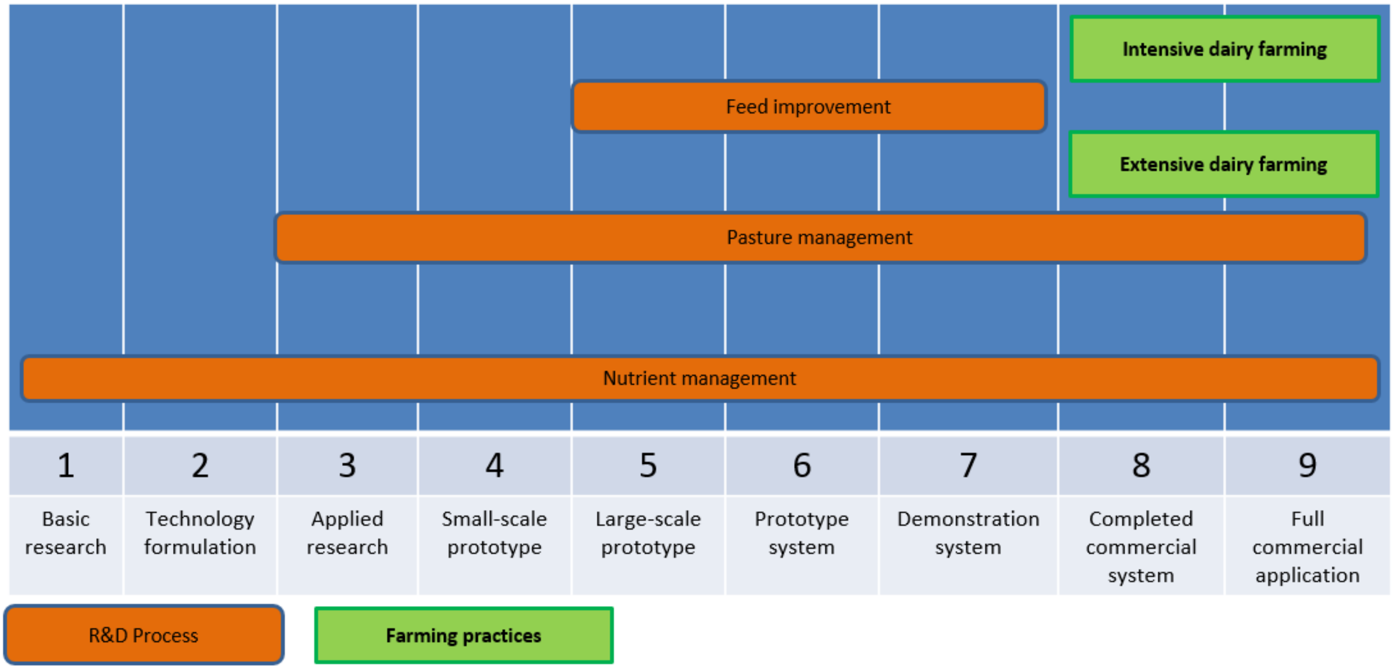


Figure 2: *Technology readiness levels of conventional and organic milk production*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Milk is produced worldwide and milk cow breeds have adapted to a wide range of environmental conditions. **S2.** The milk production industry is very mature and the processes of milk production and conversion are well understood.	**W1.** The production of milk requires large amounts of biomass and the digestion of feedstock by cows. This process releases large amounts of methane, a potent greenhouse gas.
O1. The use of mixed breeds or insemination of milk-producing varieties by beef varieties could help to decrease the environmental footprint of the combined beef and dairy industries.	**T1.** Stringent targets to reduce greenhouse emissions from agriculture would likely negatively affect the industry.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

- Cradle to farm gate includes feed production, cow feeding, milking operation, cooling for storage and manure management.

The majority of published studies on the environmental impact assessment of dairy activities make distinctions only between conventional (grouping together extensive and intensive systems) and organic systems. The results presented in Table 1 therefore represent the environmental indicators associated with the production of milk under conventional and organic farming practices. To account for variability in the fat and protein content of different milk sources, the functional unit chosen was a kg of fat- and protein-corrected milk (FPCM). 1 kg FPCM = 1 kg milk * (0.337 + 0.116 * Fat% + 0.06 * Protein%) [1]. Studies that apply energy-corrected milk (ECM) as a functional unit were excluded, because the conversion from ECM to FPCM could not be made due to the lack of data on milk protein and fat content. The most widely reported impact categories are climate change, acidification, eutrophication, land transformation and the primary energy balance. Few or no results were found for other impact categories.

Environmental assessment: settings & impacts

Table 1: LCA result for different milk production methods in the European Union. Functional unit in kg FPCM. System boundaries: cradle to farm gate

Agricultural practices	Conventional	Organic
References	[2-18]	[6, 11, 14-16]
Geographical coverage	Germany, Ireland, France, Italy, the Netherlands, Sweden, Portugal	France, the Netherlands, Sweden
Impact categories from Environmental Sustainability Assessment methodology		
Climate change (kg CO_2-eq.)	0.74 - 1.88	0.9 - 1.5
Additional impact categories		
Acidification (kg SO_2–eq.)	$6.9E^{-3}$ - $1.9E^{-2}$	$6.8E^{-3}$ - $1.6E^{-2}$
Eutrophication – aquatic (kg PO_4-eq.)	$3.4E^{-3}$ - $1.1E^{-2}$	$5.0E^{-3}$ – $7.0E^{-3}$
Land Transformation (Land use) (m^2)	0.73 - 3.79	1.8 - 2.82
Primary energy balance (MJ)	2.19 – 5.0	3.1

The normalisation presented in Figure 3 was performed using the normalisation factors provided in the JRC 2014 methodology [19] and ReCiPe normalisation values (see explanatory factsheet).

Comments and interpretation of the environmental performance (Table 1 and Figure 3)

- On a normalised scale, eutrophication represents the most important environmental impact of milk production for the EU-28, mainly because of nutrient leakage associated with effluent management.
- The lowest impacts on land transformation, eutrophication and acidification (similar to organic system in France[6]) were reported for conventional seasonal grass-based systems in Ireland [3]. This system also had the fourth lowest impact on climate change.
- The environmental impact varies between the worst and the best performers by a multiplying factor of three for climate change, acidification and eutrophication, and by a

multiplying factor of six for land transformation. However, no other clear distinctions, either geographical or by type of system (organic or conventional), were identified.

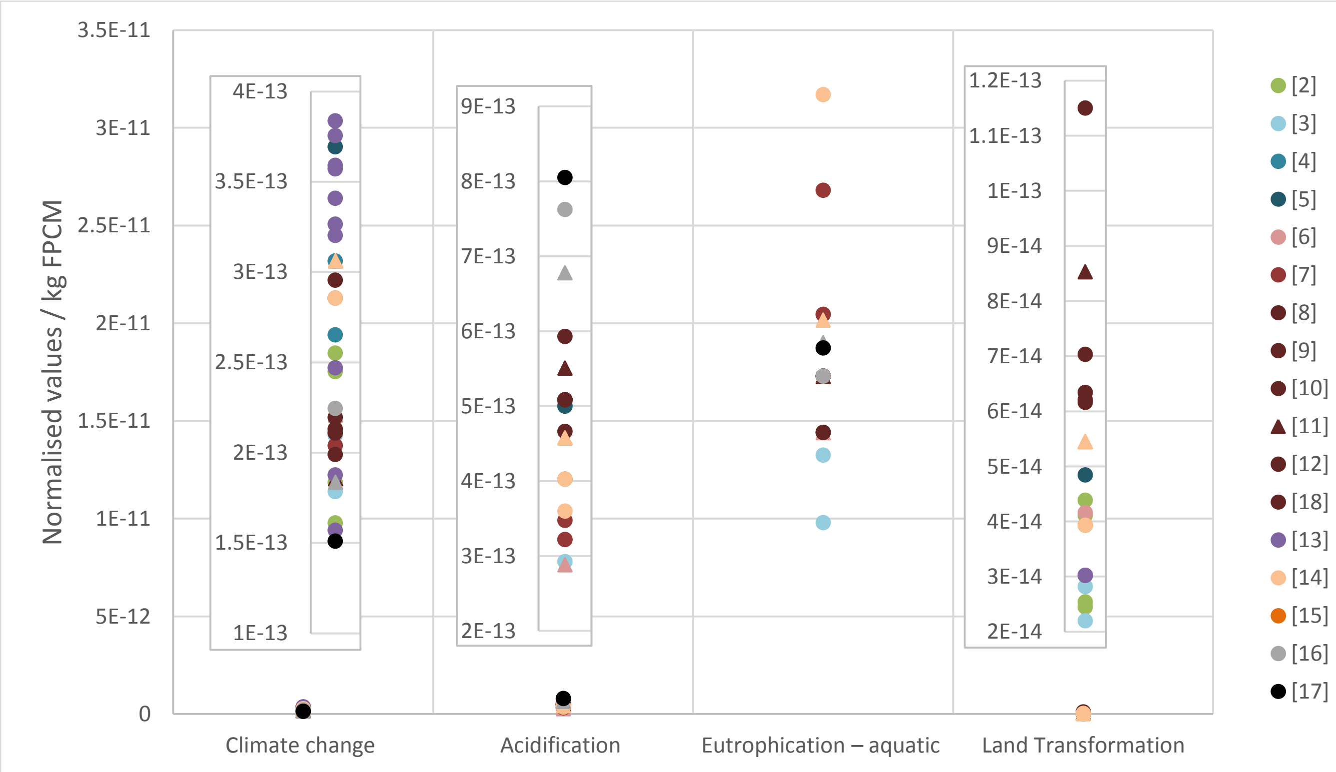


Figure 3: *Environmental performance expressed as normalised impact categories. Circles correspond to conventional dairy farming, while triangles represent organic practices. Green shades are used for Germany, blue for Ireland, red for France, purple for Italy, orange for the Netherlands, grey for Sweden and black for Portugal.*

REFERENCES / FURTHER INFORMATION

[1] Yan et al., 2011. *Journal of Environmental Management*, 92(3):372-379.
[2] Zehetmeier et al., 2014. *Agricultural Systems*.
[3] O'Brien et al., 2012. *Agricultural Systems*, 107:33-46.
[4] Casey and Holden, 2005. *Journal of Environmental Quality*, 34(2):429-436.
[5] De Boer, 2003. *Livestock Production Science*, (80):69-77.
[6] van der Werf et al., 2009. *Journal of Environmental Management*, 90(11):3643-3652.
[7] Kanyarushoky et al., Environmental evaluation of cow and goat milk chains in France. In: *6th International Conference on Life Cycle Assessment in the Agri-Food Sector 2008; Zurich, Switzerland*.
[8] AGRIBALYSE, 2014. Lait de vache,conventionnel, systeme specialise de plaine de l'ouest, mais dominant, In. ADEME.
[9] AGRIBALYSE, 2014. Lait de vache,conventionnel, systeme specialise de plaine de l'ouest, herbe-mais, In. ADEME.
[10] AGRIBALYSE, 2014. Lait de vache,conventionnel, systeme specialise de plaine, herbe, In. ADEME.
[11] AGRIBALYSE, 2014. Lait de vache,biologique, systeme specialise de plaine de l'ouest, herbe, In. ADEME.
[12] AGRIBALYSE, 2014. Lait de vache,Moyenne nationale, In. ADEME.
[13] Guerci *et al*, 2014. *Journal of Cleaner Production*, 73:236-244.
[14] Thomassen et al., 2008. *Agricultural Systems*, 96(1-3):95-107.
[15] Arvanitoyannis et al., 2014. *Critical Reviews in Food Science and Nutrition*, 54(10):1253-1282.
[16] Cederberg and Mattsson, 2000. *Journal of Cleaner Production*, 8(1):49-60.
[17] González-García et al., 2013. *Science of the Total Environment*, 442:225-234.
[18] AGRIBALYSE, 2014. Lait de vache,conventionel, systeme specialise de montagne, Massif Central, herbe, In. ADEME.
[19] JRC Report, 2014. Normalisation method and data for Environmental Footprints, In.: European Commission, Joint Research Centre; 92.

ENVIRONMENTAL FACTSHEET: ***Wheat***

PRODUCT INFORMATION

Wheat (*Triticum spp*) is the world's third most produced cereal (651 million tonnes worldwide in 2010). It is a major staple food worldwide as well as a source of animal feed (42% of wheat production was used as feed in 2007 in the EU-27). A large number of wheat varieties are available, each producing grains of variable colour, shape, starch type and quantity (50 to 80%) as well as protein content (between 9 and 23%). Local growing conditions and fertilisation regimes also have an impact on the grain's chemical composition.

Wheat varieties are usually classified as:

1. **Winter wheat** (planted in autumn and frost resistant) or **spring wheat** and
2. "**Hard wheat**" (with a higher protein content), typically used for making pasta, or "**soft wheat**", typically used for making breads and cakes.

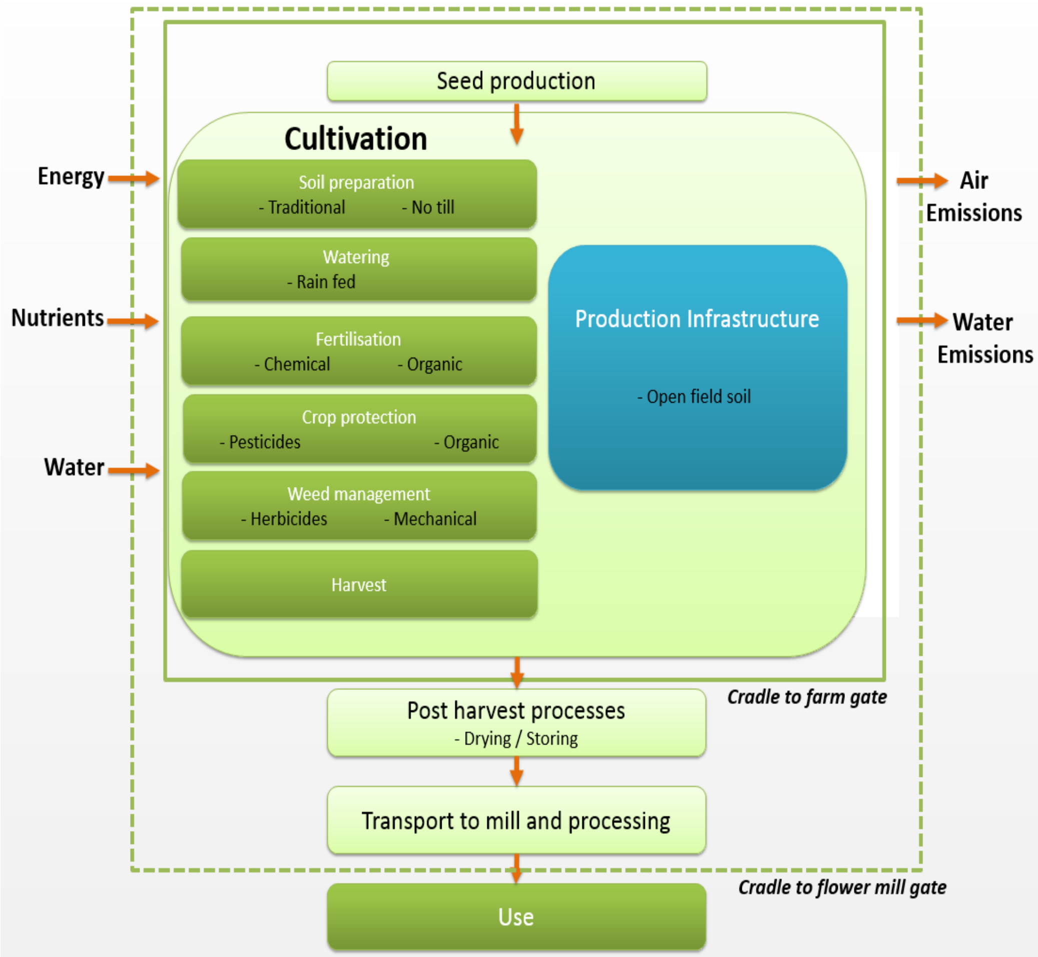


Figure 1: *wheat production chain and system boundary*

EU production: 284 million tonnes (2013).

Co-products: wheat straw, grain husk.

Two types of wheat are grown at the EU scale:
- Durum wheat (a hard wheat variety) and
- Common wheat (soft wheat).

Both can be cultivated using conventional (making use of chemical fertilisers, herbicides and pesticides) or organic farming practices (making use of organic manure, pest and parasite traps, oil sprays and mechanical control of weeds). The processes involved in wheat cultivation are detailed in Figure 1.

Wheat production in Europe is mainly rain-fed and does not usually require irrigation.

While both conventional and organic wheat farming practices are in operation at full commercial scales, conventional practices are dominant. The technology readiness levels of different activities for both conventional and organic practices are presented in Figure 2. Conventional wheat-growing practices require the use of chemical fertilisers which can be expensive. Ongoing research on crop rotations - alternating wheat with nitrogen fixing legumes - has the potential to decrease costs. No-till soil-management practices, which avoid the negative impact of ploughing the soil, are also being tested and have the potential to decrease the environmental footprint (by retaining water and soil carbon, and decreasing soil erosion) of conventional practices. Much less research has been conducted in the organic wheat farming area compared to conventional farming, and current efforts focus on new varieties development, selections and field trials. The management and control of insect pests and weeds is also a major limiting factor to organic wheat farming practices, and is the focus of numerous research activities.

Technology Readiness Levels

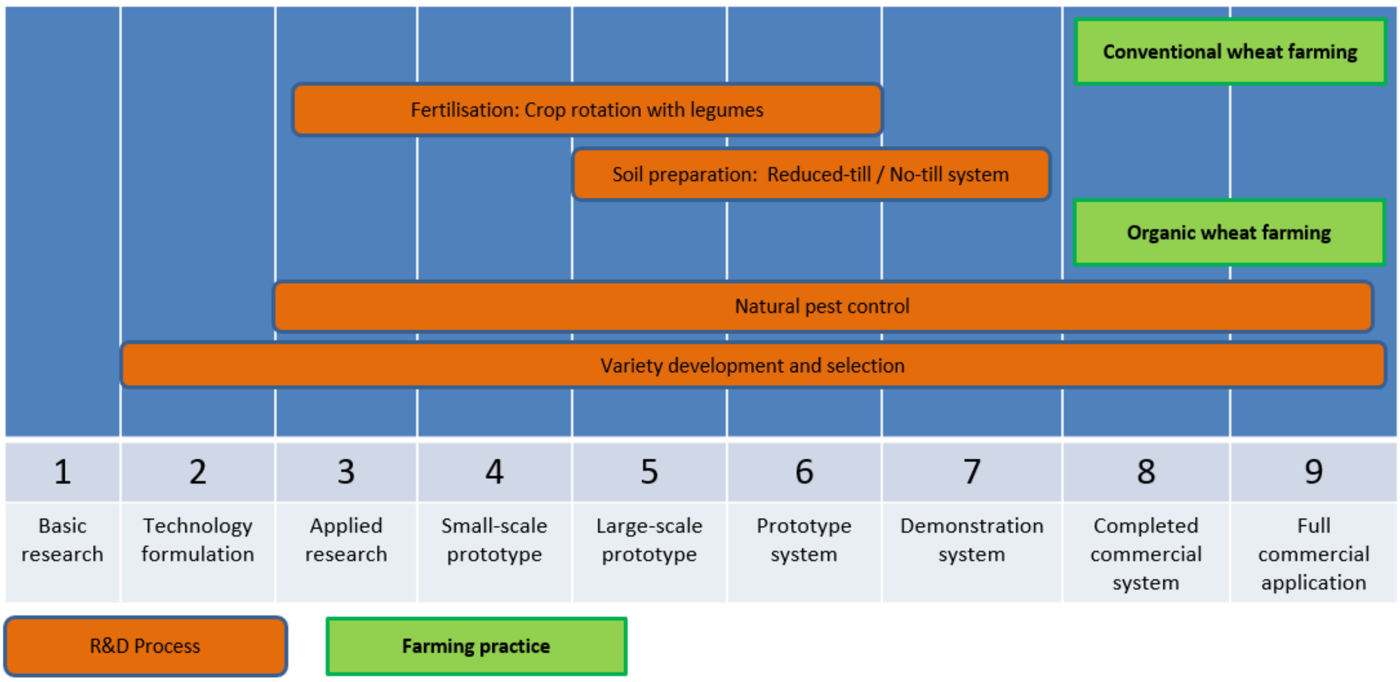


Figure 2: *Technology readiness levels for conventional and organic wheat production*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. A wide range of wheat cultivars is available and more are continually being developed. **S2.** Wheat physiology and genetics are very well understood and its response to various environmental conditions can be modelled.	**W1.** Conventional cultivation methods are heavily reliant on pesticides and inorganic fertilisers derived from fossil fuels. **W2.** The cultivation of wheat via organic methods leads to lower yields than conventional practices.
O1. New wheat varieties currently being developed (in particular those issuing from genetic engineering technology) may have the potential to increase yields and/or decrease environmental footprints. **O2.** The use of wheat straw as input to bio-refineries could increase its profitability.	**T1.** Climate change and the emergence of new pests and diseases could decrease yields. **T2.** Wheat protein content is likely to decrease under higher CO_2 levels, which could be problematic to processing activities that use high-gluten wheat (bread making).

European Commission

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

1. **Cradle to farm gate** includes seed production cultivation (fertilisers, pesticides) and the harvest.

2. **Cradle to flower mill gate** includes the same elements as cradle to farm gate, plus post-harvest processing and transport to the flour mill.

The results presented in Table 1 represent the environmental indicators associated with the production of winter wheat (under conventional and organic farming practices) and spring wheat. The most widely reported impact categories are Climate change, Acidification and Eutrophication. Few or no results were found for the other impact categories.

Environmental assessment: settings & impacts

Table 1: LCA result for different wheat varieties and cultivation methods in the European Union. Functional unit: 1 kg of wheat grain

Wheat type	Winter wheat				Spring Wheat
Agricultural practices	**Conventional**	**Conventional**	**Organic**	**Organic**	**Conventional**
References	[1-7]	[8]	[9, 10]	[8]	[11]
Geographical coverage	UK, France, Australia	USA	France	USA	Norway
System boundaries	Cradle to farm gate	Cradle to flower mill gate	Cradle to farm gate	Cradle to flower mill gate	Cradle to farm gate
Impact categories from Environmental Sustainability Assessment methodology					
Climate change (kg CO_2-eq.)	0.12 - 0.49	0.28	0.22 - 0.61	0.24	0.74
Ecotoxicity for aquatic fresh water (CTUe)	0.68 - 1.7	N.A.	-6.81 – 3.13	N.A.	N.A.
Additional impact categories					
Acidification (kg SO_2-eq.)	$7.5E^{-4} – 6.0E^{-3}$	N.A.	$1.0E^{-3} – 5.0E^{-3}$	N.A.	$2.6E^{-2}$
Eutrophication – aquatic (kg PO_4-eq.)	$1.0E^{-4}$ - $2.3E^{-3}$	N.A.	$1.0E^{-3}$	N.A.	$4.3E^{-4}$

The normalisation presented in Figure 3 was performed using the normalisation factors provided in the JRC 2014 methodology [12] and ReCiPe normalisation values (see explanatory factsheet).
N.A.: Not Available.

Comments and interpretation of environmental performance (Table 1 and Figure 3)

- The normalisation of impact values for the categories climate change, acidification and eutrophication (Figure 3) indicates that wheat cultivation has proportionally higher impacts on eutrophication than on climate change and acidification. This is due to the fact that wheat plants cannot make use of the totality of fertilisers applied, which leads to the leaching of nutrients into waterways. Higher eutrophication values are found for [9] and [10]; these are biased because wheat cultivation was considered in rotation with nitrogen fixing fava beans and lucerne, which are responsible for higher nutrient leaching than wheat alone.
- High variability in impact values for Ecotoxicity was reported by [9, 10] (Table 1) which looked at wheat being grown in rotation with fava beans (associated with the lowest ecotoxicity values) and lucern (associated with the higher values).

- Both climate change and acidification impacts vary by a factor of 10 across studies. This variability can be explained by the type of management practices considered as well as by the boundary of each study. Studies investigating optimal nitrogen management practices ([1, 4]) report low emissions in both CO_2 and SO_2 equivalents.

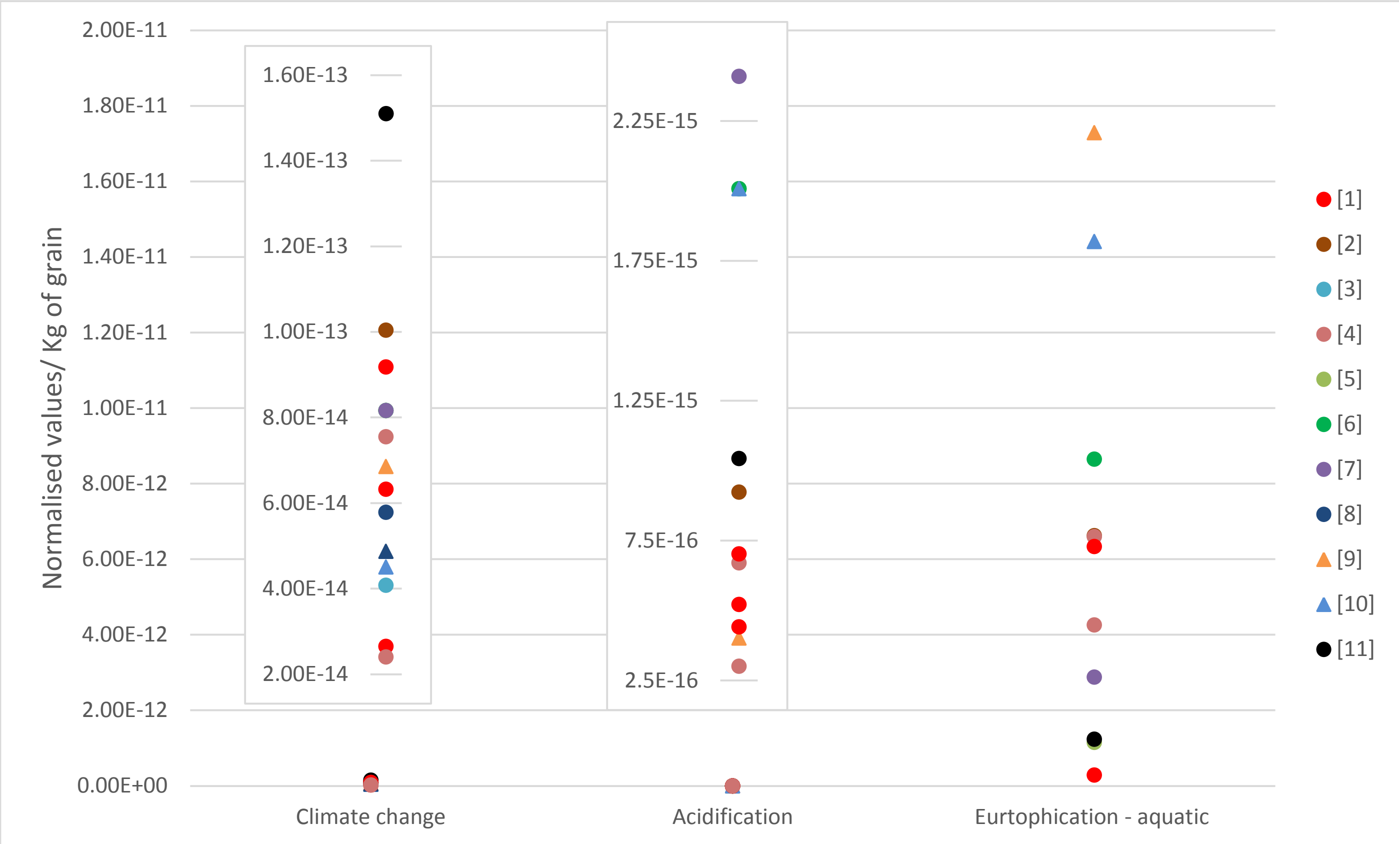


Figure 3: *Environmental performance expressed as normalised impact categories. Circles represent conventional farming practices and triangles indicate organic practices.*

REFERENCES / FURTHER INFORMATION

[1] Brentrup et al., 2004. European Journal of Agronomy, 20(3):265-279.
[2] Martinez-Hernandez et al, 2013. Biomass and Bioenergy, 50:52-64.
[3] Brock et al., 2012. Crop and Pasture Science, 63(4):319-329.
[4] Naudin et al., 2014. Journal of Cleaner Production, 73:80-87.
[5] AGRIBALYSE, 2014. Ble tendre, conventionel -Moyenne nationale, In. ADEME.
[6] AGRIBALYSE, 2014. Ble dur, conventionel -Moyenne nationale, In. ADEME.
[7] AGRIBALYSE, 2014. Ble tendre, conventionel, panifiable, 15% humidite, In. ADEME.
[8] Meisterling et al., 2009. Journal of Cleaner Production, 17(2):222-230.
[9] AGRIBALYSE, 2014. Ble tendre biologique de feverole (cas type), region Centre, In. ADEME.
[10] AGRIBALYSE, 2014. Ble tendre biologique de luzerne (cas type), region Centre, In. ADEME.
[11] Roer et al., 2012. Agricultural Systems, 111:75-84.
[12] JRC Report, 2014. Normalisation method and data for Environmental Footprints, In.: European Commission, Joint Research Centre; 92.

ENVIRONMENTAL FACTSHEET: **Wine**

PRODUCT INFORMATION

Wine is an alcoholic beverage produced from the fermentation of grapes. Wine is produced in most European countries, and the cultivation of grapes and the wine-making process represent major economic activities. Wine is typically composed of water, ethanol, glycerol, acid (tartaric, malic, lactic and acetic), phenols and tannins.

Three main types of wines (red, white and sparkling) are produced from a wide range of grape varieties. The chemical composition of wines is influenced by the types of grape, the type of soil and climate they are cultivated in, as well as by the vinification method used.

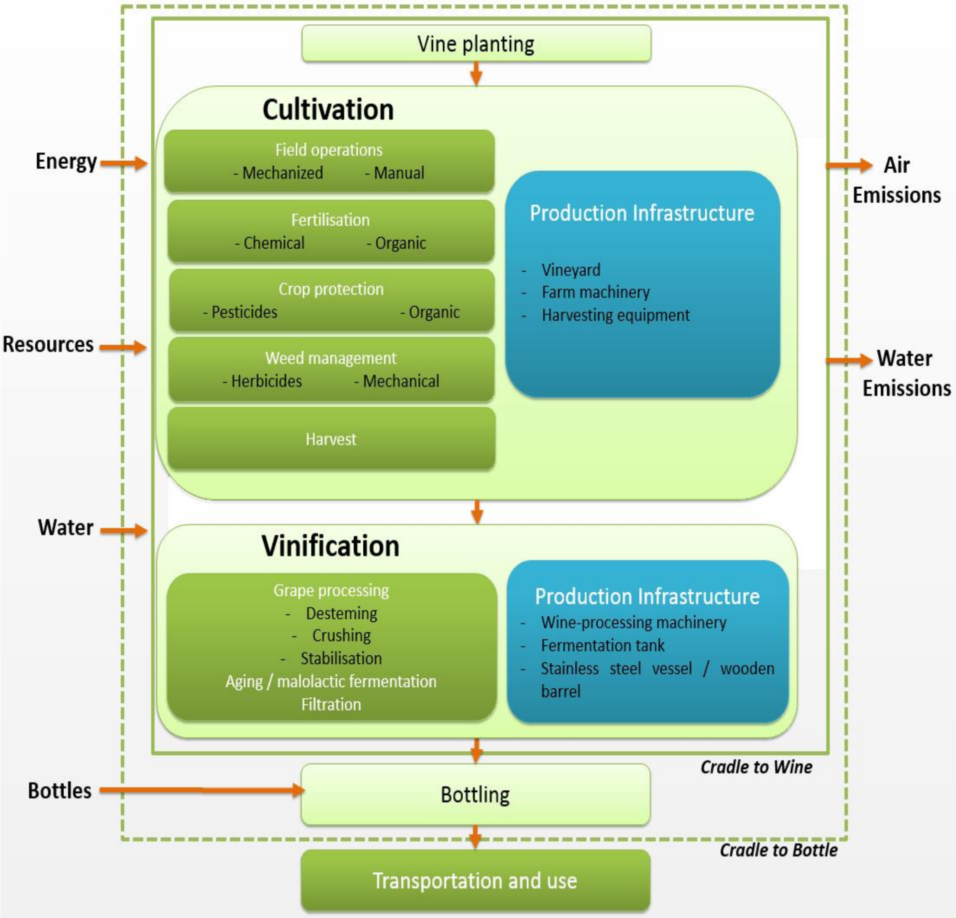


Figure 1: *wine production chain and system boundary*

EU production: 15.7 million litres (2012).

Co-products: grape stalks, pomace, grape seeds, yeast lees and vine prunings.

Grape cultivation and wine making (vinification) are composed of multiple processes (detailed in Figure 1). Grapes can be produced using conventional (making use of chemical fertilisers, herbicides and pesticides) or organic farming practices (making use of organic manure, pest parasites and controlling weeds using mechanical means). Grape irrigation is not commonly used in the EU.

While both conventional and organic grape cultivation practices are in operation at full commercial scale, conventional grape cultivation is still dominant. The technology readiness levels of different activities of grape farming and vinification are presented in Figure 2. Current research and development efforts in conventional grape cultivation focus on precision farming, which offers the potential to decrease inputs of water and nutrients (by providing only what is needed at the individual plant level), and to reduce harvesting costs. The management of grape vine pests and diseases in conventional systems requires the extensive use of pesticides. Integrated pest management techniques, which encourage natural pest control mechanisms and minimise the use of pesticides, are constantly being tested. New methods to better control weeds and pests are also being developed for organic grape farming.

The vinification process is similar in both organic and conventional wine production and consists of two successive fermentations: (1) a yeast-based alcoholic fermentation, which converts sugar to ethanol, and (2) a bacteria-driven malolactic fermentation, where malic acid is converted to lactic acid. New strains of wine yeasts are being investigated at the technology formulation and application levels, by (1) selecting strains of yeasts that are naturally present on grapes, and (2) engineering yeast genomes. Strains of modified yeasts that can be used instead of bacteria for malolactic fermentation are already available. New bio-rector technologies (such as immobilised cell reactors) that allow for faster and more efficient fermentation are also being investigated.

Technology Readiness Levels

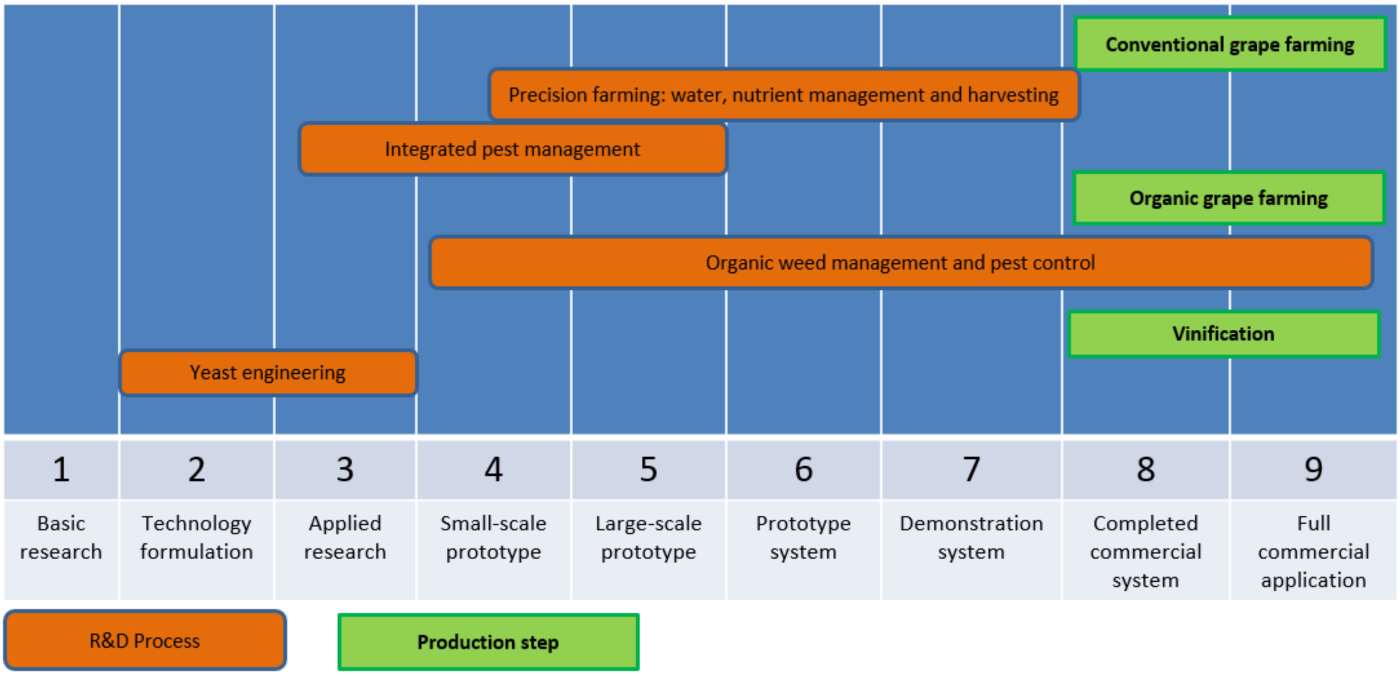


Figure 2: *Technology readiness levels for conventional and organic grape farming as well as for vinification*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Grape cultivation and wine making are very mature activities, and all steps of the process are well understood and controlled. **S2.** Research and development in wine making is very active.	**W1.** Traditional wine making requires a lot of inputs in terms of energy, management and chemical treatment. **W2.** The cultivation of grapes via organic methods leads to lower yields than conventional practices. **W3.** Emissions associated with wine packaging and transports are significant.
O1. Alternative pest control methods borrowed from organic practices (such as integrated pest management) have the potential to decrease pesticide use. **O2.** The selection and development of new strains of yeasts could lead to improvement in the wine-making process and the development of new wine types.	**T1.** Climate change is likely to shorten the maturation period of grapes, and therefore to alter the quality of wines. In the long term it may also lead to a northern shift in the range of suitable wine-growing regions which could present a major threat to the industry.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

1. **Cradle to wine**: includes vine planting, grape cultivation (fertilisers, pesticides) and vinification.

2. **Cradle to bottle**: includes the same elements as cradle to wine plus bottle production and the bottling process.

The environmental indicators of the production of wine (under both conventional and organic farming practices) are shown in Table 1. The most widely reported impact categories are climate change, ozone depletion, ecotoxicity, acidification, eutrophication and land transformation. Few or no results were found for the other impact categories.

Environmental assessment: settings & impacts

Table 1: LCA result for different grape types and cultivation methods. Functional unit 0.75 l of wine

Study boundary	Cradle to wine		Cradle to bottle	
Agricultural practices	Organic	Conventional	Organic	Conventional
References	[1, 2]	[1-5]	[2, 3]	[2, 3, 5]
Impact categories from Environmental Sustainability Assessment methodology				
Geographical coverage	Italy, Spain	Italy, Portugal, Spain	Spain, Italy, Portugal, Romania, New Zealand	Italy, Portugal, Spain
Climate change ($kgCO_2eq$)	$8.41E^{-2}$ - 0.44	0.33 - 2.24	0.49 - 1.09	0.33 - 2.68
Ozone depletion (kg CFC-11-eq.)	$8.41E^{-9}$ - $1.26E^{-8}$	$5.13E^{-8}$ – $3.45E^{-7}$	N.A.	$3.93E^{-7}$
Ecotoxicity of aquatic fresh water (CTUe)	0.27 - 0.34	0.2675	N.A.	N.A.
Additional impact categories				
Acidification (kg SO_2-eq.)	$7.4E^{-4}$ – $1.49E^{-3}$	$2.36E^{-3}$ – $1.01E^{-2}$	N.A.	$1.41E^{-2}$
Eutrophication – aquatic (kg PO_4-eq.)	$2.0E^{-4}$ - $2.7E^{-4}$	$4.89E^{-4}$ – $7.67E^{-3}$	N.A.	$7.96E^{-3}$
Land Transformation (m^2)	1.8-2.45	1.05-1.11	N.A.	1.24

N.A.: Not Available.

The normalisation presented in Figure 3 was performed using the normalisation factors provided in the JRC 2014 methodology [6] and ReCiPe normalisation values (see explanatory factsheet).

Comments and interpretation of the environmental performance (Table 1 and Figure 3)

- The highest impact, when normalised with the total values emitted in EU, is reported to be on eutrophication (Figure 3), mainly due to the use of chemical fertilisers in conventional grape-growing practices.
- There is large variability in the reported impacts of conventional wine practices on climate change (by a multiplying factor of eight), ozone depletion (by a multiplying factor of six) and acidification (by a multiplying factor of four). This can be explained by differences in management practices for different wine types and by variations in climatic conditions from year to year (e.g. drier years do not favour fungal infections, and require less application of fungicides).
- Organic grape growing and wine making practices lead to lower emissions associated with eutrophication, acidification and climate change, but to a higher level of land transformation, mainly due to the lower yields compared to conventional practices.

- Reference [5] reported the highest emissions for eutrophication, acidification, ozone depletion and high values for climate change. These extreme values were presumably linked to a higher degree of mechanisation of agricultural procedures in the production of their focus wine, and to the use of different types and quantities of fertilisers compared to other studies.

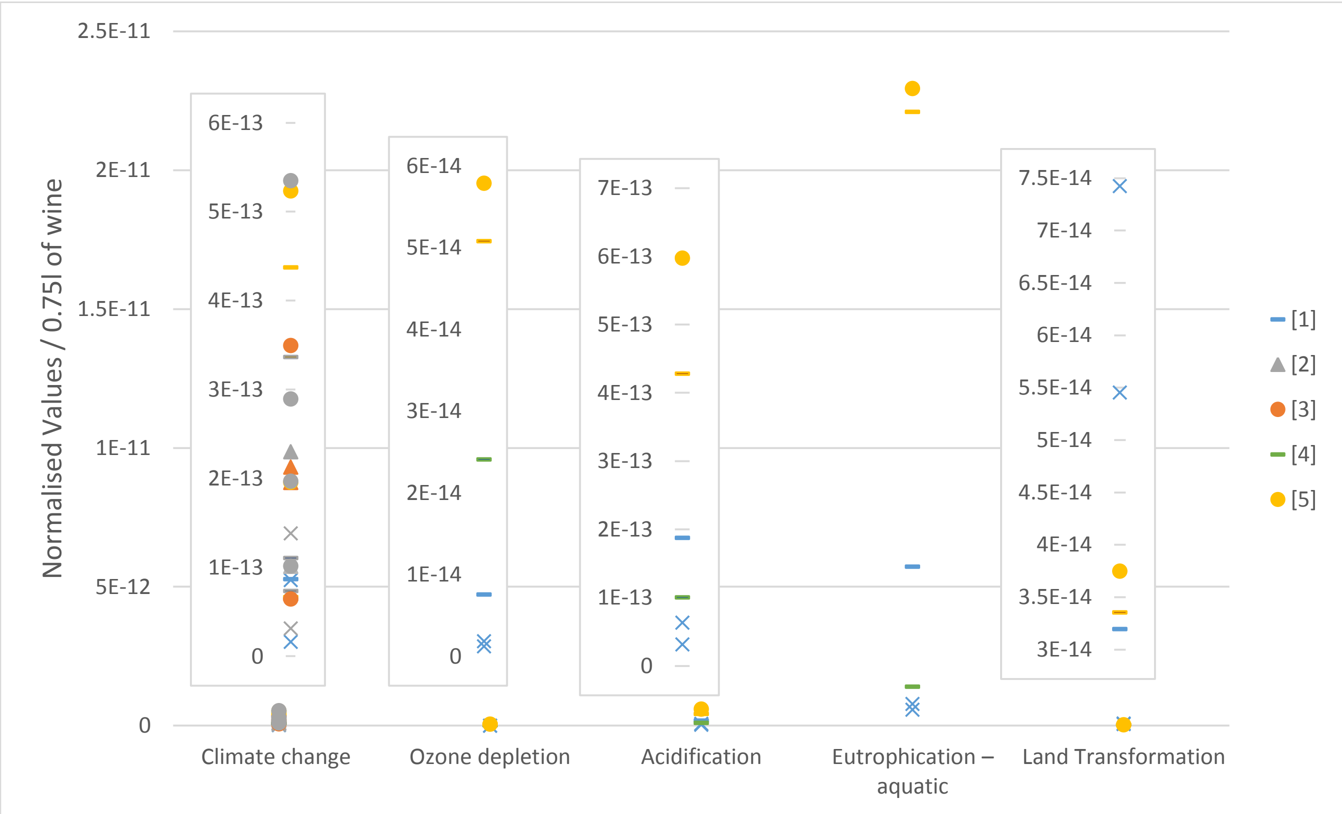


Figure 3: Environmental performance expressed as normalised impact categories. Crosses represent organic practices, horizontal bars represent conventional practices within the cradle-to-wine study boundary, circles represent conventional farming practices, while triangles indicate organic practices for cradle-to-bottle study boundaries.

REFERENCES / FURTHER INFORMATION

[1] Villanueva-Rey *et al*, 2014. *Journal of Cleaner Production*, 65:330-341.
[2] Vázquez-Rowe *et al*, 2013. *Journal of Cleaner Production*, 43:146-155.
[3] Rugani *et al*, 2013. *Journal of Cleaner Production*, 54:61-77.
[4] Fusi *et al*, 2014. *Science of the Total Environment*, 472:989-1000.
[5] Neto *et al*, 2013. *International Journal of Life Cycle Assessment*, 18(3):590-602.
[6] JRC Report, 2014. Normalisation method and data for Environmental Footprints, In.: European Commission, Join Research Center; 92.

Bio-based Products Pillar

ENVIRONMENTAL FACTSHEET: ***1,3-Propanediol***

PRODUCT INFORMATION

1,3-propanediol (1,3-PDO) is a bifunctional organic compound with the chemical formula $OHCH_2CH_2CH_2OH$. 1,3-PDO is a building block chemical that can be used in the preparation of the bio-based polymer polytrimethylene and in the production of adhesives, paints, resins and coatings.

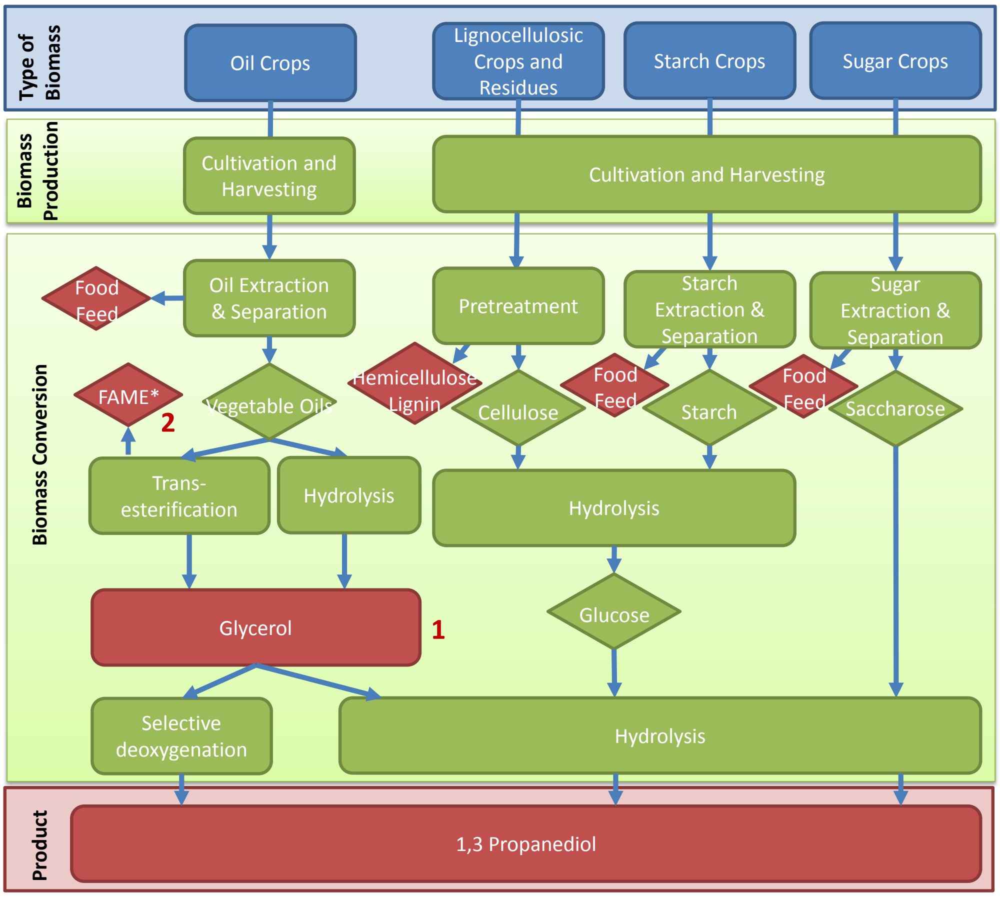


Figure 1. *1,3-PDO production chains*
**FAME: Fatty acid methyl esters (biodiesel)*

1,3-PDO can be chemically synthesised from fossil-based compounds such as propenal or ethylene oxide. Most 1,3-PDO production is thought to come from the hydroformylation of ethylene oxide.

The bio-based pathways include the fermentation of glycerol (see glycerol factsheet[1]) or the fermentation of sugars. Therefore, 1,3-PDO can be produced from a range of sugar or starch biomass crops, lignocellulosic materials, oil crops and residues. The maturity of various 1,3-PDO production technologies is summarised in Figure 2. The use of lignocellulosic materials appears to be the least advanced production system. The sugar fermentation path is commercially available using the genetically modified bacteria *E. Coli.* Glycerol is a by-product of biodiesel production (see biodiesel via transesterification factsheet[2]) and can be fermented to produce 1,3-PDO using bacteria such as *Klebsiella pneumonia*, *Clostridium butyricum* and *Citobacter freundii* [1]. However, the use of mixed bacterial cultures has also been proposed.

1,3-PDO can also be chemically synthesised by selective deoxygenation (or selective reduction) of glycerol using organometallic catalysts.

After fermentation, the commercially available process for separating 1,3-PDO from the fermentation broth consists of micro- and ultra-filtration, ion exchange separation, evaporation and distillation.

Technology Readiness Levels

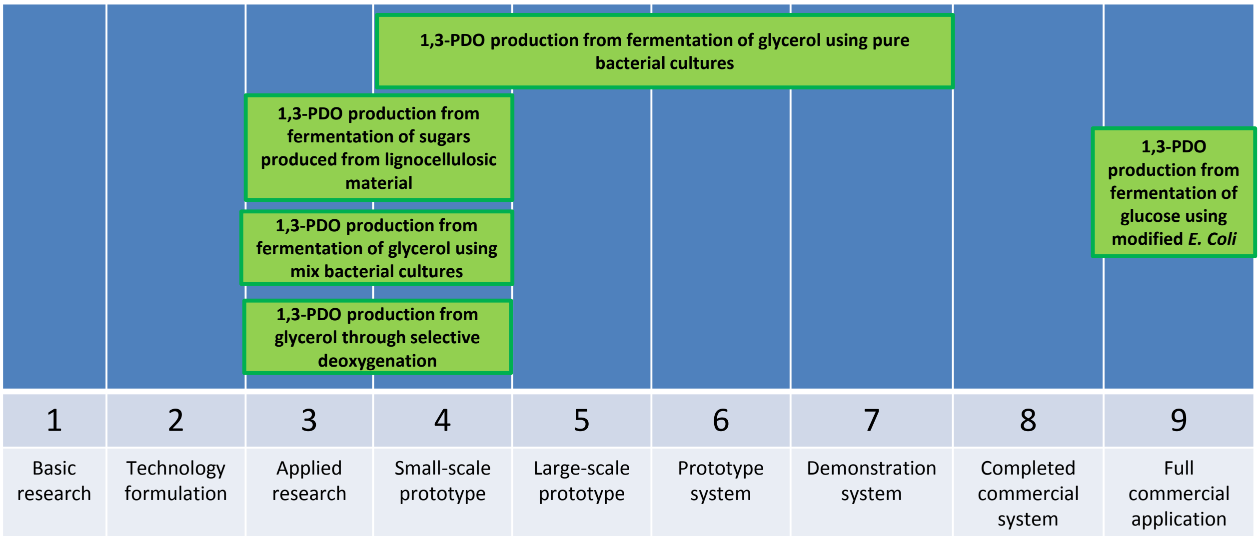


Figure 2. *Technology readiness levels for 1,3-PDO production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. The bio-based production pathway is already at full commercial scale. **S2.** 1,3-PDO has a wide variety of applications which results in increasing demand for this product.	**W1.** Glycerol production pathway has low yields and is inhibited by both substrate and product. **W2.** Difficult recovery of 1,3-PDO from fermentation broth.
O1. The increased availability of glycerol may boost the development of the glycerol fermentation pathway.	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses.

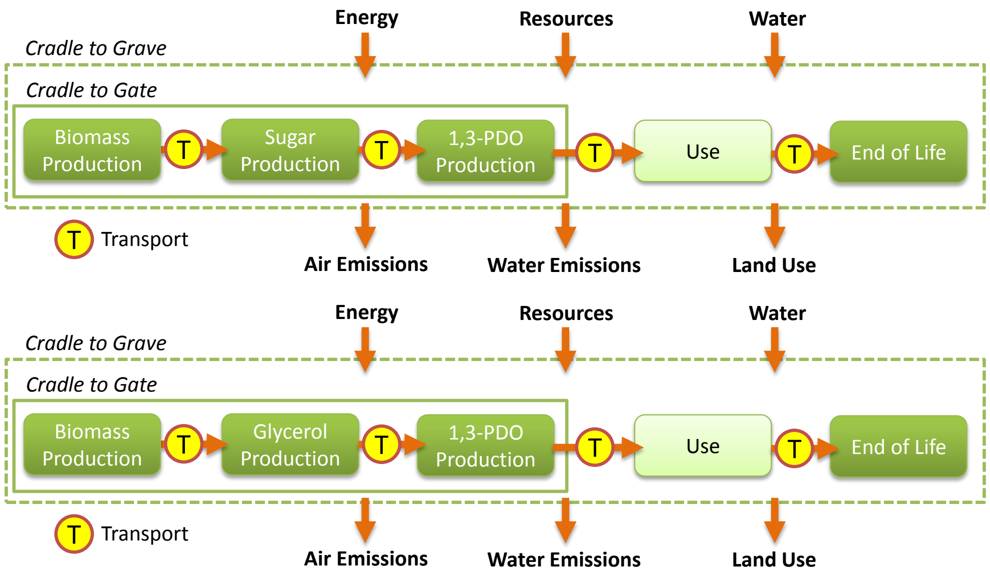
ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of 1,3-PDO is summarised in Table 1, based on the available relevant LCA data for 1,3-PDO production, using different raw materials (corn, sugar cane, corn stover and rapeseed) through: 1. aerobic fermentation of sugars, or 2. anaerobic fermentation of glycerol and 3. purification through evaporation, crystallisation and distillation.

Most of the values reported in the literature were calculated using the cradle-to-gate (see Figure 3) LCA approach. When the cradle-to-grave approach is considered [2], the climate change results are found to increase by up to 80%, depending on the specific end-of-life scenario (the extreme case considers incineration without energy recovery or capture of CO_2 in the agriculture phase).

The most widely reported impact categories are climate change, land use, primary energy and non-renewable energy use. Few or no results were found for the remaining impact categories of the environmental sustainability assessment methodology developed in the context of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment



1. **Cradle to gate:** includes the resource extraction (energy, materials and water), transport and the production steps until the gate of the 1,3-PDO factory.
2. **Cradle to grave:** in addition to the cradle-to-gate activities, this system includes the transport and distribution of the product, the use of 1,3-PDO and its end-of-life stage.

Figure 3. *LCA system boundaries for 1,3-PDO production and end-of-life stage*

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of 1,3-PDO in a cradle-to-gate system

Raw material input	Corn	Sugar Cane	Corn stover	Rapeseed
Allocation/substitution	A($-m), S	A($-m), S	A($-m), S	A($-m), S
Geographical coverage	EU and US	Brazil	EU	EU
References	[2,3*]	[2]	[2]	[2]
Impact categories from Environmental Sustainability Assessment methodology				
Climate change (kg CO_2-eq.)	(0.5-2.8)	(-1.7-(-)0.4)***1***	(-0.8-0.4)***2***	(1.7-1.8)***4***
Freshwater eutrophication (kg PO_4-eq.)	$4.5E^{-3}$ [3]	N.A.	N.A.	N.A.
Additional impact categories				
Freshwater ecotoxicity (kg 1,4-DB-eq.)	$1.26E^{-7}$ [3]	N.A.	N.A.	N.A.
Human toxicity – no cancer effects (kg 1,4-DB-eq.)	$1.8E^{-2}$ [3]	N.A.	N.A.	N.A.
Photochemical ozone formation (kg C_2H_4-eq.)	$1.7E^{-3}$ [3]	N.A.	N.A.	N.A.
Acidification (kg SO_2-eq.)	$4.5E^{-2}$ [3]	N.A.	N.A.	N.A.
Marine ecotoxicity (kg 1,4-DB-eq.)	$3.9E^{-4}$ [3]	N.A.	N.A.	N.A.
Terrestrial ecotoxicity (kg 1,4-DB-eq.)	$8.1E^{-7}$ [3]	N.A.	N.A.	N.A.
Land use (m^2)	(2.7-3.1) [2]	(2.8-3.2)	(1.1-1.3)***3***	(4.2-5.3) ***4***
Primary energy (MJ)	(79.7-95.2) [2]	(93.0-108.6)	(83.0-98.5)	(96.8-105.5) ***4***
Non-renewable energy (MJ)	(37.6-54.6)	(-8.6-14.5) ***1***	(11.9-32.3) ***2***	(62.8-63.5) ***4***

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System Expansion.
*The agriculture yields used in these studies correspond to data collected before 2008.

The normalisations presented in Figure 4 were performed using the normalisation factors provided by the JRC methodology [4] and the ReCiPe normalisation factors (see explanatory document).

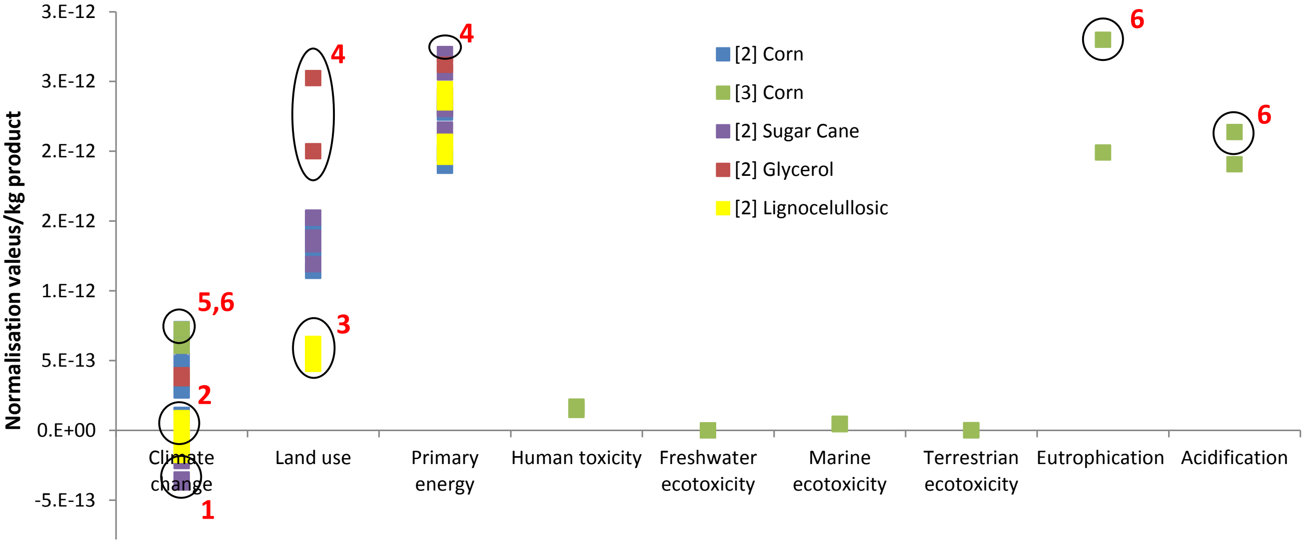


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table1 and Figure 4)

1. The lowest impact values found for climate change and non-renewable energy demand were obtained for the production of 1,3-PDO from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [2] for the energy surplus, generated from bagasse burn;
2. Reference [2] considers the burning of lignin-rich waste (obtained in the pre-treatment by hydrolyses (see bioalcohols via fermentation factsheet) of corn stover) to produce power and heat. This results in decreased impacts in demand for non-renewable energy and climate change categories;
3. The land requirements for 1,3-PDO production using corn stover are lower than those of corn, sugar cane and glycerol. This is mainly due to the economic allocation applied (used for dividing the impacts between two products) [2], which assigns a lower value to corn stover than to corn kernels;
4. The environmental impacts of producing 1,3-PDO from glycerol are usually higher than those of the other feedstock pathways, because glycerol earns lower fermentation yields and requires higher land use per kg of end product;
5. The highest values found for climate change impacts were obtained from studies which took into account cradle-to-grave system boundaries [2]. It can be therefore concluded that the end-of-life phases are environmentally significant, depending on the chosen end-of-life option;
6. Reference [3] reports LCA results using allocated and non-allocated values. In Table 1 only the allocated ones are reported, while in Figure 4 the non-allocated ones are marked with point 6. Higher values were found when no allocation was applied, compared to the use of mass allocation. This observation indicates the importance of allocation for the final result. Environmental impact results, however, decrease when substitution is applied, as in this case the system is credited for the production of by-products (see comments 1 and 2).

REFERENCES / FURTHER INFORMATION

[1] Kraus, 2008. Clean 36: 648 – 651.
[2] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/
[3] Urban et al., 2009. Ind. Eng. Chem. Res. 48: 8068–8082.
[4] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC
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ENVIRONMENTAL FACTSHEET: **Glycerol**

PRODUCT INFORMATION

Glycerol is a chemical compound with three hydroxyl groups. It is widely used in pharmaceutical, health care and food industries, and is a by-product of biodiesel (see biodiesel via transesterification factsheet) production. It can be produced through chemical syntheses from propylene. However, owing to the increased production of biodiesel, the bio-based pathway has become more important. Bio-based glycerol is mainly produced by hydrolysis or the transesterification of oils and fats (see Figure 1). Hydrolysis is typically performed at high pressures and temperatures. Transesterification is the reaction between an oil/fat and an alcohol (such as methanol) to produce esters and glycerol in the presence of a catalyst. Different types of catalysts may be used: alkaline or acid catalysts, homogeneous or heterogeneous catalysts, and enzymes. Supercritical transesterification can also be applied without the presence of a catalyst.

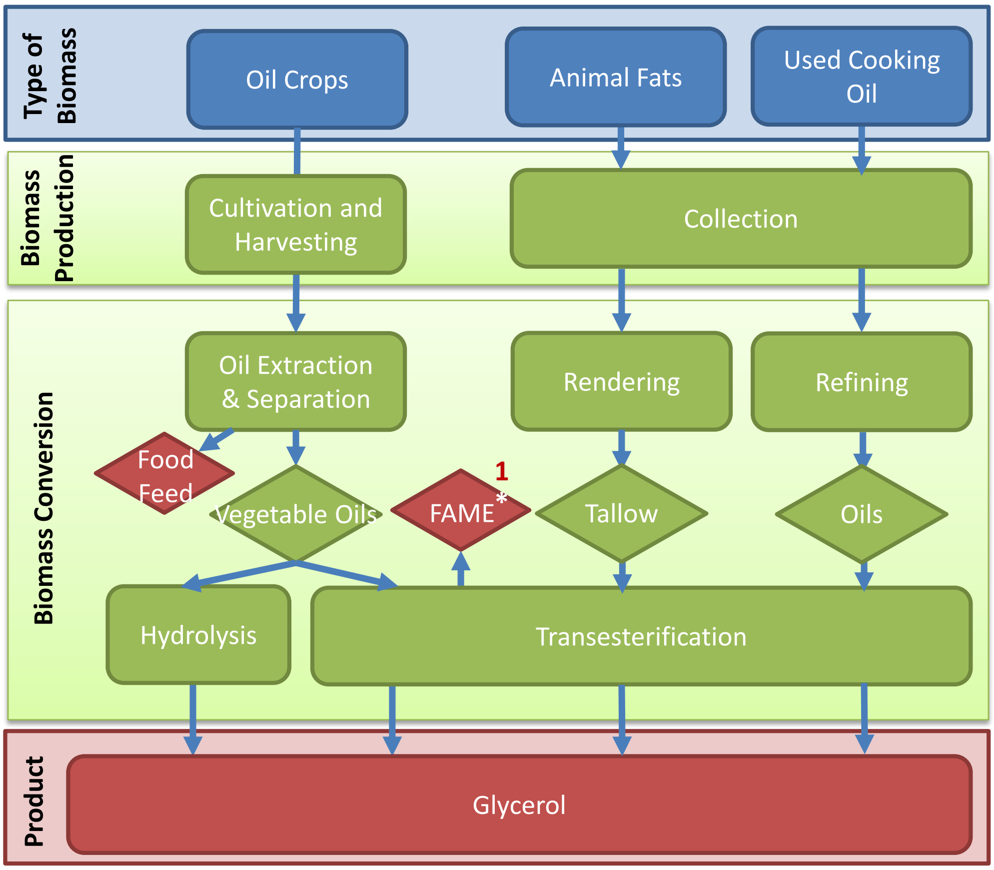


Figure 1. *Glycerol production chains *FAME-Fatty acid methyl esters (biodiesel)*

Homogeneous alkaline catalysis is the conventional method commonly used in industry. The use of an alkaline catalyst allows for short reaction times and high efficiencies when low concentrations of free fatty acids are present in the raw oil/fat. Free fatty acids are converted into soaps under alkaline catalysis. Glycerol purification is energy intensive when a homogeneous catalyst is used. The purification involves several steps: (1) distillation (for methanol recovery), (2) neutralisation of the catalyst, (3) separation by decantation of waste streams, and (4) further purification of the glycerol by distillation to remove water and methanol. The use of homogeneous acid catalysis permits the conversion of oils/fats with high content of free fatty acids.

However, the reaction is slow and the presence of water limits the conversion of oils/fats into esters and glycerol. Heterogeneous and enzyme catalyses have the advantage of simplifying the separation and purification of glycerol, and decreasing production costs and generated waste. The use of enzymes as a catalyst for transesterification requires less energy, but also slows reaction times.

The use of supercritical alcohol was also proposed for the transesterification of oils/fats. This method presents high conversion yields, shorter reaction times, high glycerol purity and lower amounts of waste compared to the catalytic processes. The drawbacks of the supercritical method are the high temperatures and pressures required. Glycerol can be produced from oil crops, waste oils, animal fats and microalgae/algae oils. The maturity of various glycerol production technologies is summarised in Figure 2. The use of microalgae oils appears as the least advanced production system, while the use of oil crops and animal fats are fully commercially available.

Technology Readiness Levels

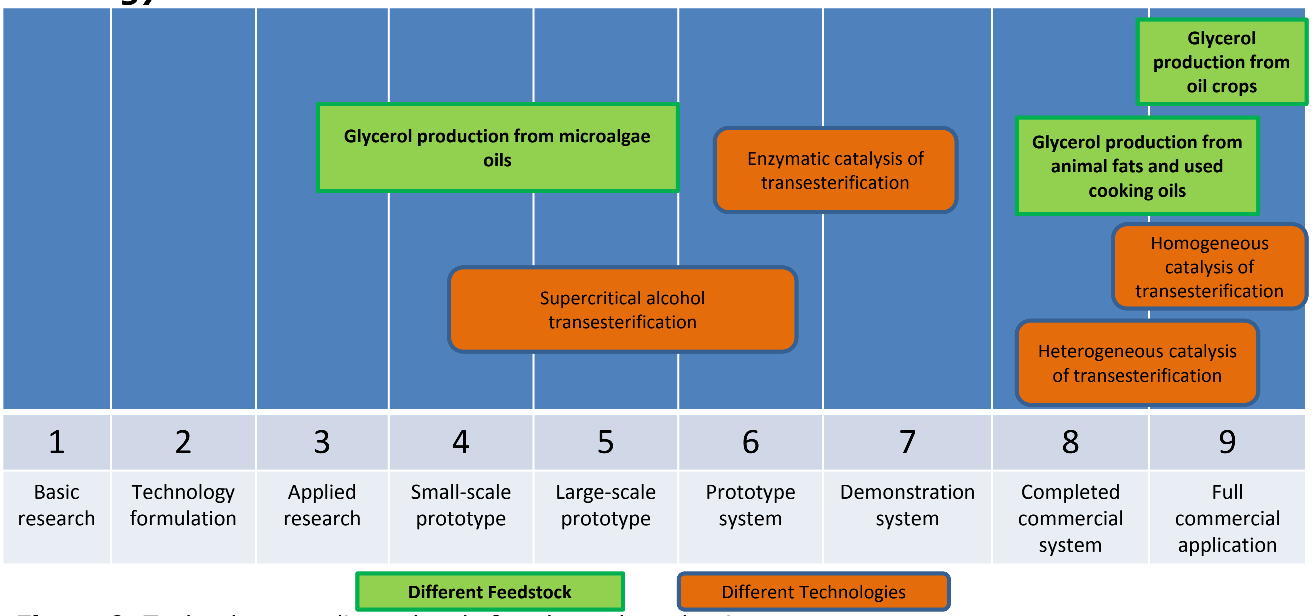


Figure 2. *Technology readiness levels for glycerol production*

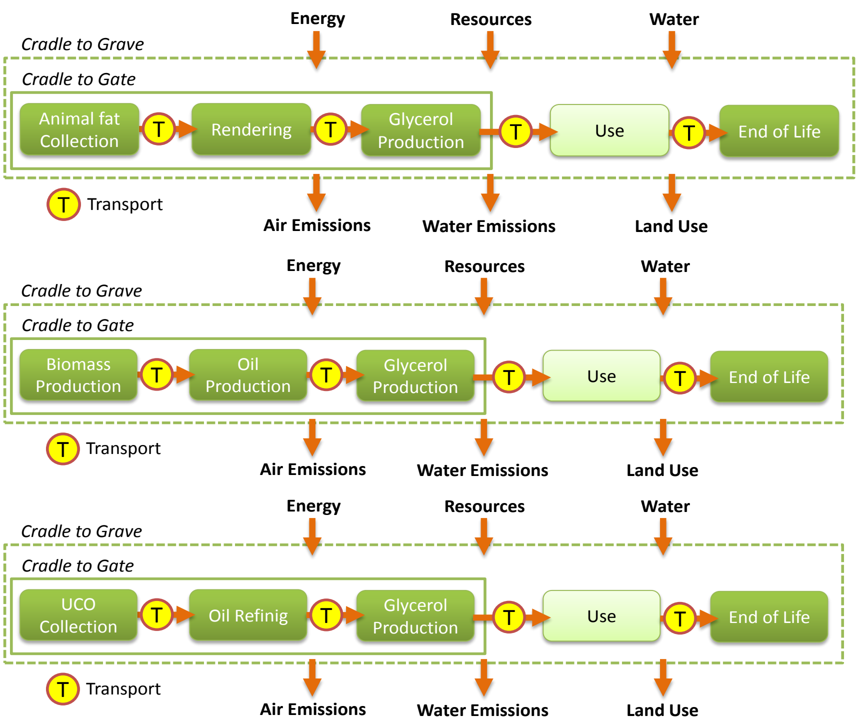
SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. Glycerol is a widely available product owing to the increased production of biodiesel worldwide.	**W1.** Glycerol purification is an expensive process. **W2.** The conventional production process has high production costs and generates significant environmental drawbacks.
O1. Further developments of glycerol purification will decrease glycerol production costs. **O2.** The development of applications for unrefined glycerol will eliminate expensive purification processes.	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses. **T2.** The increased production of glycerol as a by-product of biodiesel has lowered its market price.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of glycerol summarised in Table 1 is based on the available relevant LCA data for glycerol production using different raw materials and considering economic, mass and energetic allocation. The values reported for references [1, 3-6] were calculated from biodiesel impact results, taking into account the specific allocation assumptions described in each study. All these values were calculated using a cradle-to-gate (see Figure 3) LCA approach. The most frequently reported impact categories are climate change, eutrophication, acidification and abiotic depletion. Few or no results were found for the remaining impact categories of the environmental sustainability assessment methodology developed in the context of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment:



Cradle to gate: includes all transport and production steps until glycerol production (factory gate, including glycerol production), all waste collection and treatment steps and the resource extraction (e.g. energy, materials and water).

Figure 3. *LCA system boundaries for glycerol production and end-of-life. (UCO – used cooking oil)*

*Table 1: The authors of reference [4] considered the avoided emissions of CO_2 as a credit (to account for the carbon uptake during biomass growth), which explains the low climate change impact values.

Environmental assessment: settings & impact

Table 1. LCA results for one kg of glycerol in a cradle-to-gate system

Raw material input	Rapeseed			*Brassica carinata* (oil crop)		Palm	FFA-rich wastes
Allocation/substitution	A(m)	A(E)	A($)	A($)	A(E)	A(E)	A(m)
Geographical coverage	Spain, France, Germany	Spain, France, Germany	Spain, France, Germany	Italy		Brazil	
References	[1,3]	[1]	[1,4]	[2]		[5]	[6]
Impact categories from Environmental Sustainability Assessment methodology							
Climate change ($kg\ CO_2$-eq.)	(0.15-0.44)1	(0.10-0.13)1	($1.6E^{-3}$*-$3.7E^{-2}$)1	0.17 1	0.47 1	0.17	(0.06-0.1)2
Ozone depletion (kg CFC-11-eq.)	$8.8E^{-8}$ [3]	N.A.	$3.0E^{-9}$ [4]	N.A.	N.A.	N.A.	($7.8E^{-9}$-$2.0E^{-8}$)2
Freshwater eutrophication ($kg\ PO_4$-eq.)	($7.0E^{-4}$-$4.0E^{-3}$)1	($5.0E^{-4}$-$6.9E^{-4}$)1	($1.4E^{-4}$-$2.1E^{-4}$)1	$2.1E^{-4}$ 1	$5.7E^{-4}$ 1	$3.9E^{-4}$	($8.1E^{-5}$-1.5 E^{-4})2
Additional impact categories							
Freshwater ecotoxicity (1,4-DB-eq.)	$1.5E^{-3}$ [3]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Human toxicity (kg 1,4-DB-eq.)	$1.5E^{-2}$ [3]	N.A.	N.A.	$7.7E^{-2}$ 1	0.20 1	N.A.	N.A.
Abiotic depletion (kg Sbeq)	($5.6E^{-4}$-$1.3E^{-3}$)1	($3.4E^{-4}$-$4.3E^{-4}$)1	($9.5E^{-5}$-$2.0E^{-4}$)1	$2.6E^{-3}$ 1	$5.2E^{-3}$ 1	N.A.	N.A.
Acidification ($kg\ SO_2$-eq.)	($1.0E^{-3}$-$3.2E^{-3}$)1	($7.1E^{-4}$-$9.3E^{-4}$)1	($2.0E^{-4}$-$3.0E^{-4}$)1	$7.0E^{-4}$ 1	$2.6E^{-3}$ 1	$1.1E^{-3}$	($4.3E^{-4}$-$6.8E^{-4}$)
Photochemical ozone formation ($kg\ C_2H_4$ -eq.)	$1.5E^{-4}$ [3]	N.A.	N.A.	$3.1E^{-5}$ 1	$9.0E^{-5}$ 1	N.A.	($1.9E^{-5}$-$4.7E^{-5}$)2
Primary energy (MJ)	N.A.	N.A.	0.5 [4]	3.7 1	11.0 1	N.A	(1.2-3.8)2

N.A.: not available. A: Allocation ($-economic; E-energy; m-mass). S: Substitution. SE: System expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors from provided in the JRC methodology [7] and the ReCiPe normalisation factors (see explanatory document).

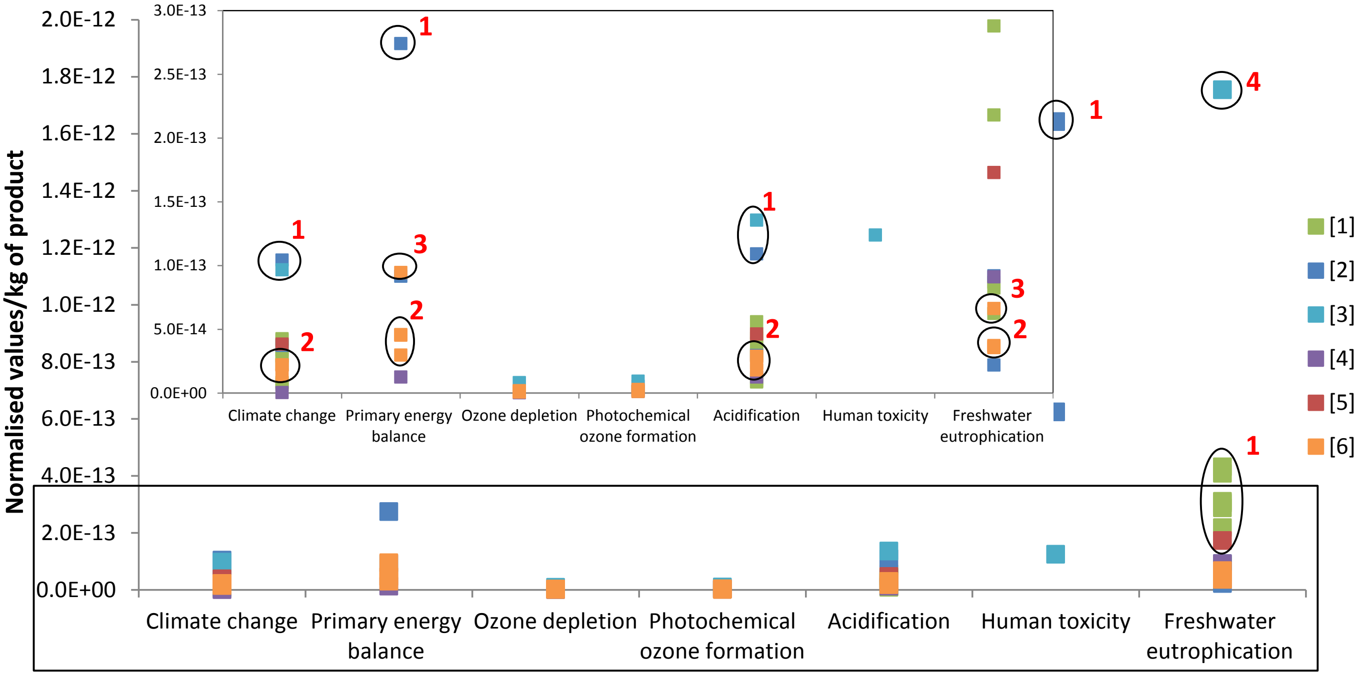


Figure 4. *. Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4)

1. Generally, the reported impacts are higher when mass (typically 8-10% is associated with glycerol) or energetic allocation (typically 4-5% is associated with glycerol) are considered against the impacts obtained using economic allocation (typically 1.1-1.5% is associated with glycerol). This observation confirms the importance of the chosen allocation method for the final results;
2. Generally, the case studies that consider waste to be re-used for the production of glycerol present lower impacts (even when mass allocation is considered), because the generation of waste products is not included in the system boundaries of glycerol production;
3. Amongst waste products that are rich in fatty acids, sewage presents higher impacts, mainly due to the lower production yields and the higher amounts of methanol needed for transesterification;
4. Amongst the reported impact categories, the highest (normalised) impacts were found for the eutrophication of freshwater. This can be explained by the use of phosphorus fertilisers during cultivation, especially in the rapeseed case study.

REFERENCES / FURTHER INFORMATION

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
4FCrops
BIOREF-INTEG
VALOR-PLUS

[1] Malça et al., 2014. Applied Energy, 114: 837–844.
[2] Fiorentino et al., 2014. J Clean Prod 66: 174-187.
[3] Harding et al., 2007. J Clean Prod 16: 1368-1378.
[4] González-García et al., 2013. Int J Life Cycle Assess, 18: 61–76.
[5] Delivand and Gnansounou, 2013. Bioresource Technol 150: 438–446.
[6] Dufour and Iribarren, 2012. Renew Energ 38: 155-162.
[7] JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

ENVIRONMENTAL FACTSHEET: ***Lactic Acid***

PRODUCT INFORMATION

Lactic acid is a hydroxycarboxylic acid $CH_3CH(OH)COOH$ with two stereoisomers (D(-) and L(+)), and has several applications in food, chemical, pharmaceutical and health care industries. It is primarily used for food and pharmaceutical applications, preferentially the L(+) isomer, since this is the only lactic acid isomer produced in the human body. Around 20 to 30% of lactic acid production is used to obtain biopolymers (polylactic acid). Other uses include the manufacture of fibres and green solvents.

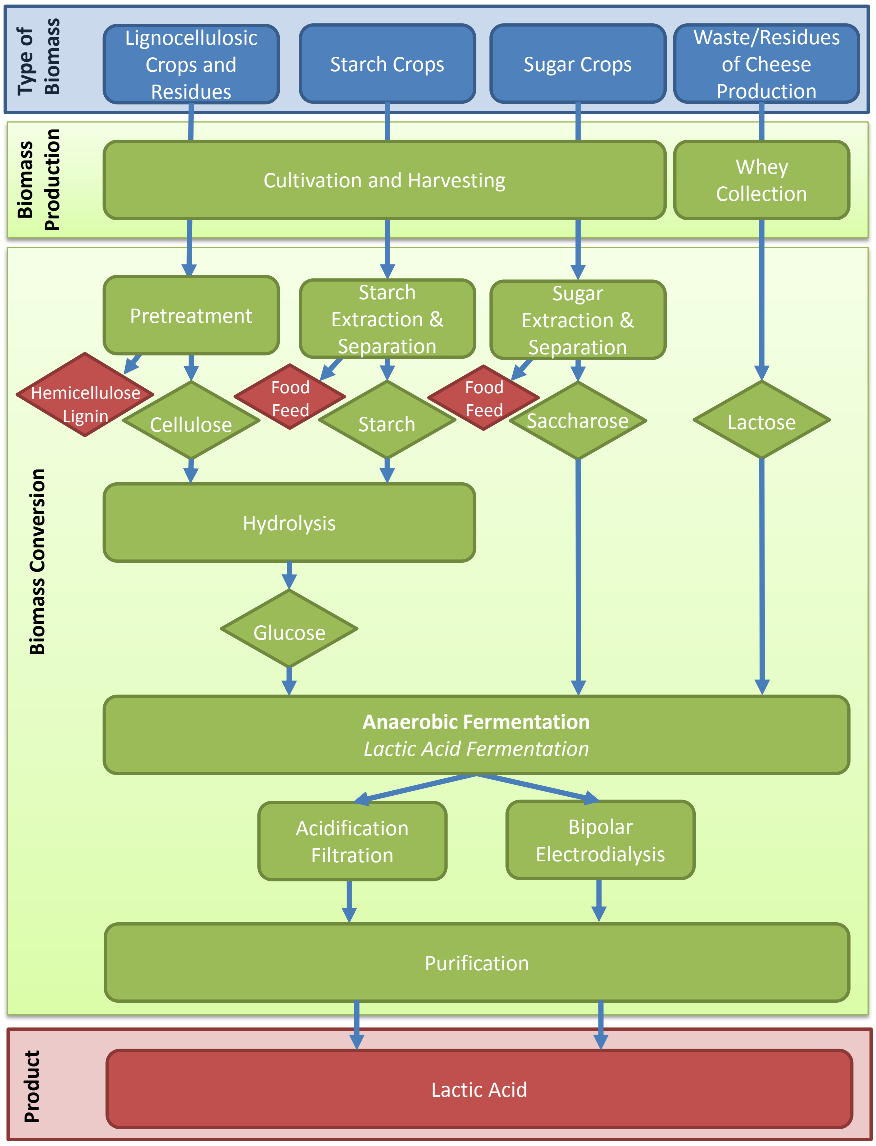


Figure 1. *Lactic acid production chains*

Lactic acid is fully commercially available and largely (90%) produced by bacteria (see Figure 1) through the anaerobic fermentation of sugars. It can also be commercially produced by chemical synthesis. The chemical production pathway gives an optical inactive racemic mixture (with the same quantity of L and D isomers), while the anaerobic fermentation pathway mostly yields one of the two stereoisomers, depending on the microorganism chosen. The biotechnological option is widely available due to its renewable origin. Lactic acid can be produced via the fermentation of sugars from different forms of biomass, such as starch crops, sugar crops, lignocellulosic materials and whey (a residue of cheese production). The maturity of various lactic acid production technologies is summarised in Figure 2. The use of lignocellulosic materials appears as the least advanced production system, while the use of sugars from starch or sugar crops is fully commercially available.

The bulk of world production is based on the homoplastic fermentation of sugars (from starch or sugar crops) where lactic acid is produced as a sole product. Previously used production systems require the addition of large amounts of calcium hydroxide to control the fermentation level of acidity (pH) to near pH7. This procedure results in calcium lactate as final fermentation product that is then acidified to lactic acid and associated with the of large amounts of chemical effluents that contain calcium sulphate (also known as gypsum). The industry R&D efforts allowed for the implementation of a fermentation technology (based on microorganisms capable of growing at lower pHs) that permits the operation at low pHs [1]. This advancement reduces: (1) the need for calcium hydroxide addition, (2) the formation of gypsum and (3) the energy for the separation process. Several steps are required to ultimately obtain and purify lactic acid, such as: filtration, acidification, carbon adsorption, evaporation, esterification, hydrolysis and distillation. New separation technologies are also considered in the literature, such as bipolar electrodialysis, with promising results.

Technology Readiness Levels

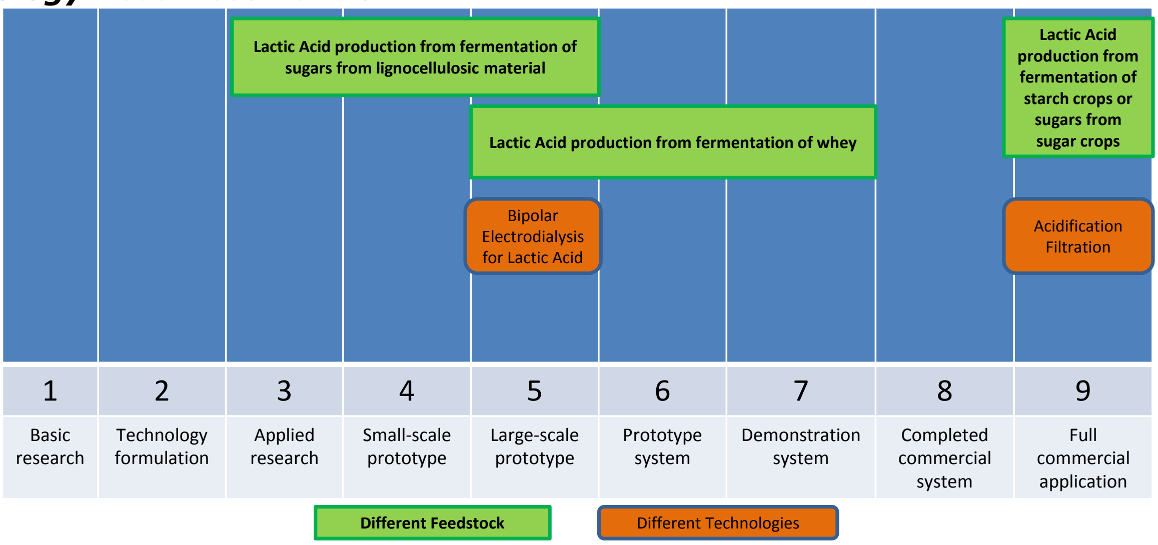


Figure 2. *Technology readiness levels for lactic acid production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. Lactic acid is produced at the full commercial scale. The bio-based production pathway is more economically and environmentally sound than the chemical one. **S2.** Lactic acid has a wide variety of applications in food, pharmaceutical and chemical industries.	**W1.** High separation and purification costs. **W2.** The previous commonly used fermentation and separation processes were connected to high costs and generation of large amounts of waste.
O1. The described developments in lactic acid fermentation and separation technologies increase the production efficiency. **O2.** A growing interest in biobased polymers such as PLA may boost the demand for (and hence, production of) lactic acid.	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of lactic acid summarised in Table 1 is based on the available relevant LCA data for lactic acid production using different raw materials (corn, sugar cane and corn stover), through the conventional lactic acid purification process: neutralisation, filtration, esterification and distillation.

Most of the values reported in the literature were calculated using cradle-to-gate (see Figure 3) LCA approach discussed in the BREW project [1]. Climate change results are also present for the cradle-to-grave system which includes incineration without energy recovery as an end-of-life scenario for lactic acid [1]. The BREW project considered the use phase in the cradle-to-grave calculations to be negligible.

For this product, the available environmental impact results were found for climate change, land use, primary energy and non-renewable energy. No results were found for the other impact categories described in the environmental sustainability assessment methodology developed in the context of of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment

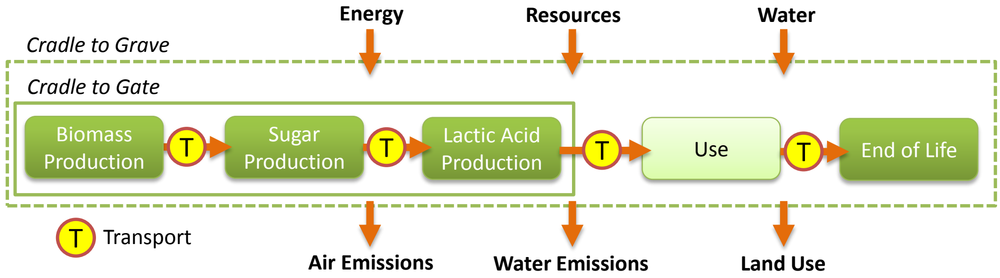


Figure 3. *LCA system boundaries for lactic acid production and end-of-life stage*

1. Cradle to gate: includes the resource extraction (energy, materials and water), transport and the production steps until the exit gate of the lactic acid factory. **2. Cradle to grave:** in addition to the cradle-to-gate activities, this system includes the transport and distribution of the product, the use of lactic acid, and its end-of-life stage.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of Lactic Acid

Raw material input	Corn		Sugar cane		Corn stover	
LCA boundaries	Cradle to Gate	Cradle to grave	Cradle to Gate	Cradle to grave	Cradle to Gate	Cradle to grave
Allocation/substitution	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S
Geographical coverage	EU	EU	Brazil	Brazil	EU	EU
References	[1*,2]	[2]	[2]	[2]	[2]	[2]
Impact categories from Environmental Sustainability Assessment methodology						
Climate change (kg CO_2-eq.)	(0.3-1.2)	(1.9-2.7)***1***	(-0.6-0.2)***2***	(0.8-1.6) ***1***	(-0.2-0.6)***3***	(1.3-2.1) ***1***
Additional impact categories						
Land use (m^2)	(1.4-2.2) [2]	N.A.	(1.4-2.2)	N.A.	(0.5-1.3)***4***	N.A.
Primary energy (MJ)	(57.8-66.1)	N.A.	(64.1-72.4)	N.A.	(53.4-67.6)	N.A.
Non-renewable energy (MJ)	(21.8-37.5)	N.A.	(9.0-15.7)***2***	N.A.	(16.4-25.4)***3***	N.A.

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System Expansion.
* Note: The LCA results from reference [1] were converted into kg of lactic acid based on a conversion yield of 1.35 kg lactic acid needed to produce one kg of PLA (information from European Bioplastics e.V., Germany).

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [2] and the ReCiPe normalisation factors (see explanatory document).

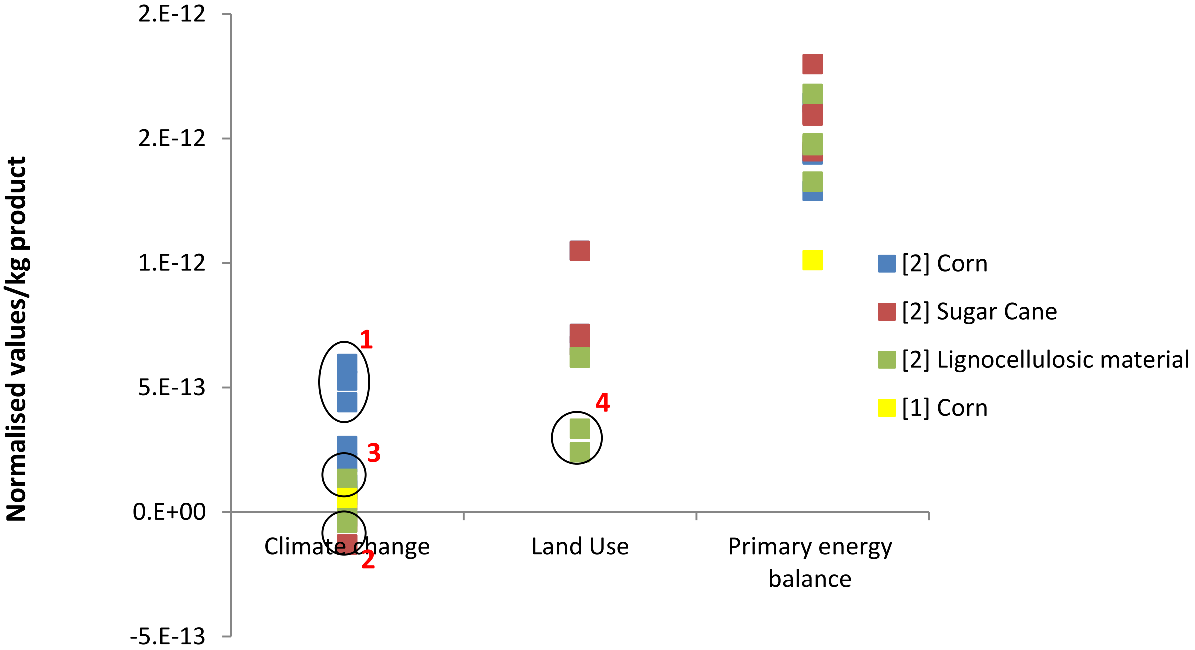


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4)

1. The highest values found for climate change were obtained from studies that consider cradle-to-grave boundaries. It can therefore be concluded that the use and the end-of-life phases are environmentally significant;
2. The lowest values found for climate change and non-renewable energy demand were obtained for the production of lactic acid from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [1] for the energy surplus, generated from bagasse burn;
3. The authors of the BREW project [1] consider the burning of lignin-rich waste (obtained in the pretreatment of corn stover using hydrolysis - see bioalcohols via fermentation factsheet) to produce power and heat. This results in reduced impacts on non-renewable energy demand and climate change;
4. Less land is required to produce for lactic acid production from corn stover than from corn and sugar cane. This is due to the economic allocation applied (used for dividing the impacts between two products) [1] that assigns a lower value to corn stover than corn kernels.

REFERENCES / FURTHER INFORMATION

[1] Vink et al., 2010. Industrial Biotechnology 6: 212-224.

[2] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/

[3] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC

ENVIRONMENTAL FACTSHEET: **Polylactic Acid**

PRODUCT INFORMATION

Polylactic Acid (PLA) is a biodegradable and biocompatible thermoplastic. It is used in the production of packaging, plastic films, bottles and fibres, and in medical applications (medical grade PLA). Due to some of PLA gas permeability properties it can be used in particular for packaging fresh food (e.g. bread, fruits and vegetables). PLA is produced from the chiral compound Lactic Acid (see lactic acid factsheet[1]). It can be synthesised into three stereochemical forms: poly-L-lactic acid (usually a semicrystalline polymer), poly-D-lactic acid (usually a highly crystalline polymer), and poly-DL-lactic acid (an amorphous polymer).

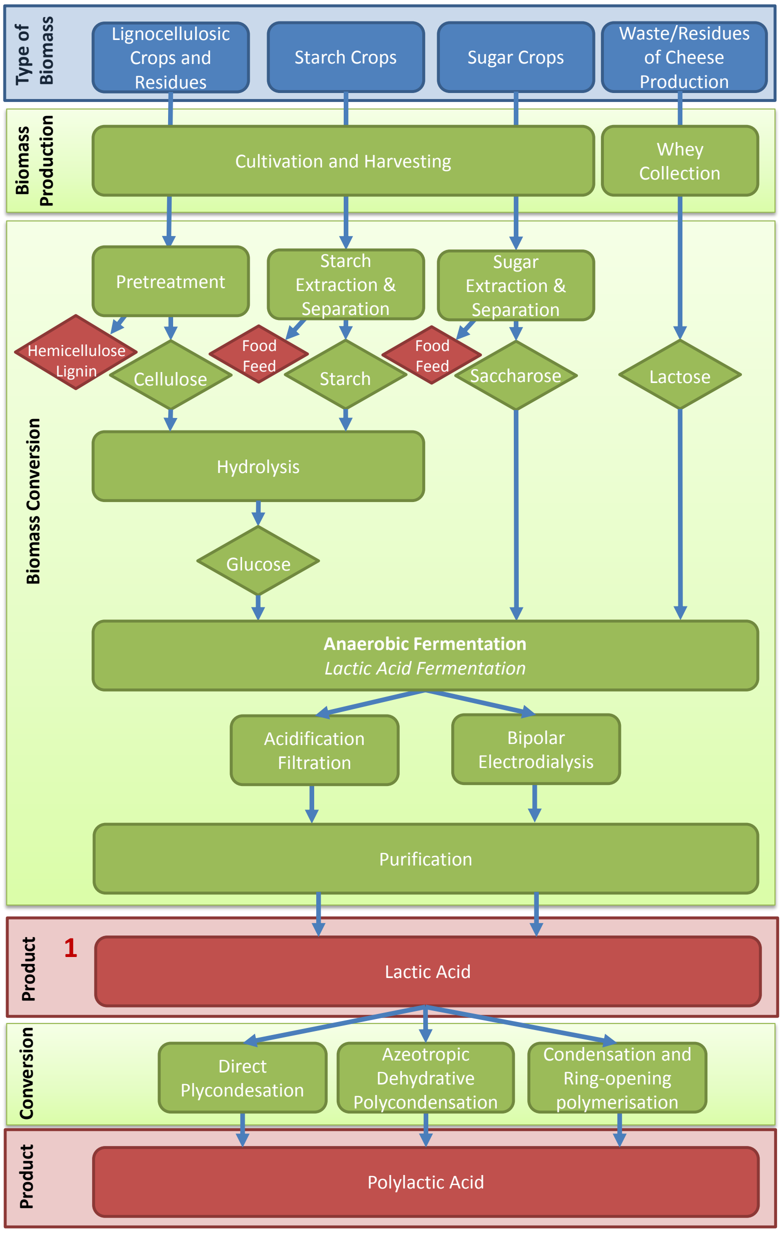


Figure 1. *Polylactic acid production chains*

The manufacturing of PLA requires the production of two intermediary products: lactic acid and sugars (such as glucose, saccharose or lactose, see Figure 1). Lactic acid (see lactic acid factsheet[1]) is produced from the fermentation of sugars which are obtained from processing different types of biomass (e.g. lignocellulosic materials, starch crops, sugar crops and whey). The maturity of various PLA production technologies is summarised in Figure 2. The use of lignocellulosic materials appears as the least advanced production pathway, while the use of sugars from starch or sugar crops is fully commercially available.

PLA is synthesised from lactic acid, mainly in two ways: a) direct polycondensation of lactic acid, and b) ring-opening polymerisation of lactide. The latter is the most common means of producing high-molecular-weight PLA, and involves condensation of lactic acid to the cyclic diester lactide, and conversion of this lactide into PLA by catalytic ring-opening polymerisation. The direct polycondensation of lactic acid only produces low-molecular-weight polymers. Higher molecular weights can also be produced by chain coupling agents (after direct polycondensation) or by the azeotropic dehydrative polycondensation of lactic acid using azeotropic solvents.

In addition to the abovementioned methods, sequential melt and solid polycondensation has also been proposed to increase the molecular weight of the PLA polymer. This process includes two polymerisation steps performed at different temperatures: above melting point and below melting point, without solvents.

Technology Readiness Levels

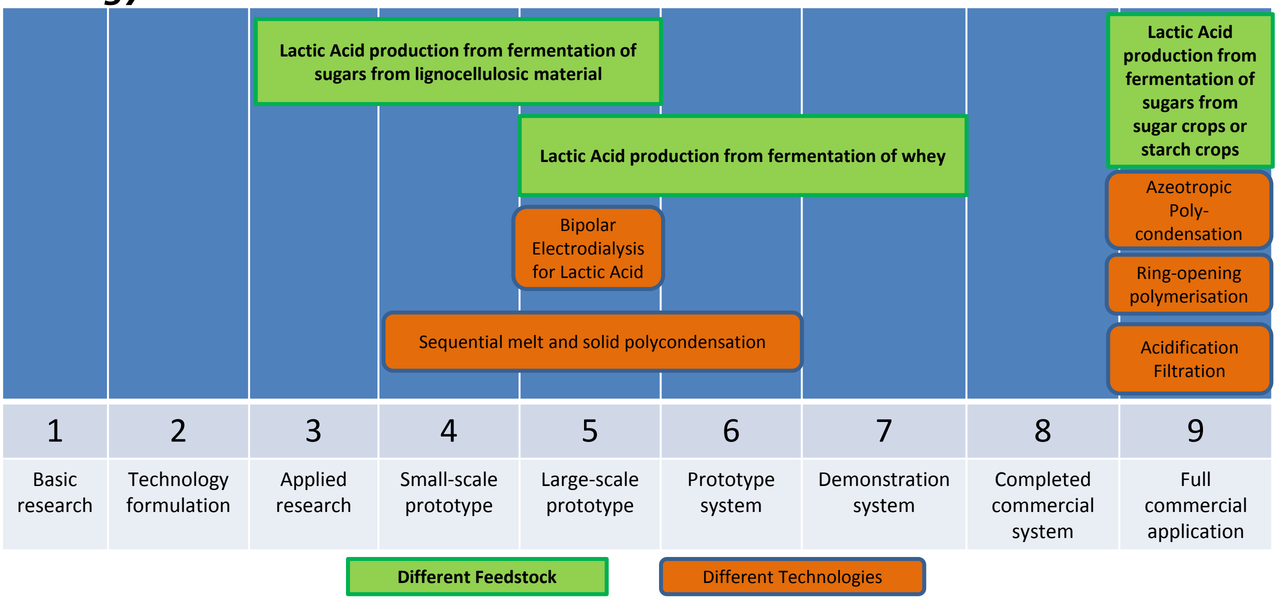


Figure 2. *Technology readiness levels for PLA production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. PLA is a biodegradable and biocompatible polymer with a high variety of uses, including disposable packaging and high added-value applications (such as medical grade PLA, subject to tighter quality, purity and regulatory controls). **S2.** PLA can replace several fossil based polymers, such as Polyethylene terephthalate.	**W1.** PLA production costs may hinder its use in lower-value applications. **W2.** PLA thermal and gas permeability are lower compared to fossil polymers. Depending on the application, this can also be seen as an advantage e.g. for fresh food packaging.
O1. Developments of new catalysts and melt polymerisation processes could reduce PLA production costs. **O2.** The possibility of producing lactic acid from waste/residues could decrease production costs. ***O3.*** Since PLA is produced from a renewable source, carbon tax systems may increase its competitiveness against fossil-based polymers.	**T1.** Biomass availability for the production of PLA due to competition with other uses. **T2.** The cost of the input material for the PLA process, lactic acid, may threaten the use of PLA in lower value applications.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of PLA summarised in Table 1 is based on the available relevant LCA data for PLA production through: 1. Ring opening polymerisation; 2. Lactic acid purification using neutralisation, filtration, esterification and distillation (see lactic acid factsheet[1]). Most of the values reported in the literature were calculated using cradle-to-gate (see Figure 3) LCA approach. When the cradle-to-grave approach is considered [1], the climate change results can increase up to 55% depending on the end-of-life scenario considered.

The most commonly reported impact categories are climate change, land use, primary energy and non-renewable energy. Few or no results were found for the other impact categories of the environmental sustainability assessment methodology developed in the context of the project "Setting up the Bioeconomy Observatory" (see explanatory document factsheet).

System boundaries of the environmental assessment

1. Cradle to gate: includes the resource extraction (energy, materials and water), transport and the production steps until the exit gate of the PLA factory. **2. Cradle to grave:** In addition to the cradle to gate activities, this system includes the transport and distribution of the product, the use of PLA and its end-of-life stage.

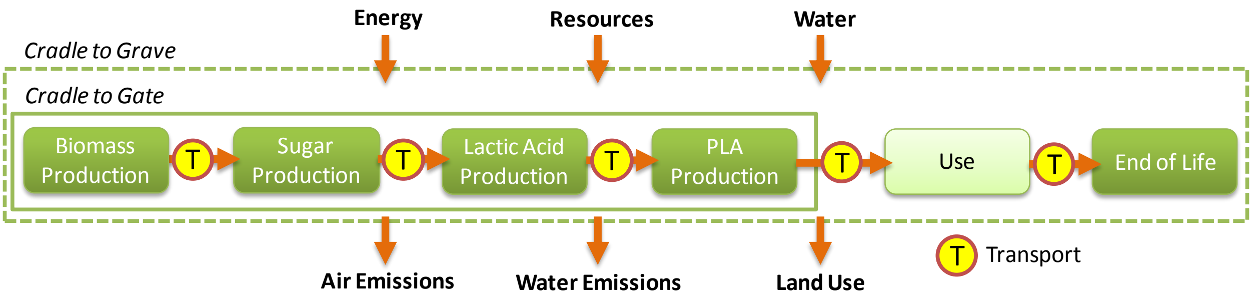


Figure 3. *LCA system boundaries for PLA production and end-of-life stage*

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of PLA in a cradle-to-gate system			
Raw material input	Corn	Sugar Cane	Corn stover
Allocation/substitution	A($-m), S	A($), S	A($), S
Geographical coverage	USA, Europe	Brazil, Thailand	USA, Europe
References	[1-9]	[1,10]	[1-2]
Impact categories from Environmental Sustainability Assessment methodology			
Climate change (kg CO_2-eq.)	(0.3)***1*** (0.6-3.2) ***2***	(-0.1-1.0)***3***	(0.5-1.5)
Ozone depletion (kg CFC-11-eq.)	($4.0E^{-10}$-$3.6E^{-7}$) [4,6,9]	N.A.	N.A.
Freshwater Ecotoxicity (CTUe)	6.5 [4]	N.A.	N.A.
Human Toxicity - cancer effects (CTUh)	$1.5E^{-7}$ [4]	N.A.	N.A.
Human Toxicity - non cancer effects (CTUh) and (kg 1,4-DB-eq.)	$7.5E^{-8}$ [4] (CTUh)	$8.5E^{-3}$ [10] (kg 1,4-DB_{eq})	N.A.
Particulate Matter/Respiratory inorganics (kg $PM_{2.5}$-eq.)	$4.4E^{-3}$ [6]	N.A.	N.A.
Acidification (mol H^+-eq.)	0.62 [4]	N.A.	N.A.
Marine Eutrophication (kg N_4-eq.)	$2.5E^{-2}$ [4]	N.A.	
Freshwater Eutrophication (kg PO_4-eq.)	($1.8E^{-4}$-$7.5E^{-3}$) [5-7,9]	$5.0E^{-3}$ [10]	N.A.
Resource depletion – water (kg of water)	(35-69.3) [2,3,9]	N.A.	N.A.
Additional impact categories			
Photochemical ozone formation (kg C_2H_4-eq.)	($6.0E^{-4}$-$1.0E^{-3}$) [7,9]	$3.4E^{-3}$ [10]	
Acidification (kg SO_2-eq.)	($7.3E^{-3}$-$3.8E^{-2}$) [5-7,9]	$2.1E^{-2}$ [10]	N.A.
Respiratory Organics (kg C_2H_4-eq.)	$4.3E^{-3}$ [6]	N.A.	N.A.
Terrestrial Eutrophication (kg PO_4-eq.)	$1.4E^{-2}$ [7]	N.A.	N.A.
Land use (m^2)	(1.7-2.8) [1,3,7]	(1.8-2.8)	(0.6-1.7)***4***
Primary energy (MJ)	(58.4)***1*** (65.8-97.4) [1-3,5-7]	(86-105.5)	(81.2-99.4) [1]
Non-renewable energy (MJ)	(27.2)***1*** (32.4-60.8) [1-3,5-9]	(21.4-32.9)***3***	(29.2)***1*** (33.8-45.3)***5***

Notes. N.A.: Not Available. A: Allocation ($-economic; E-energy; m-mass). S: Substitution. SE: System expansion.

From references [5] and [6], the environmental results presented in the Table 1 refer only to the PLA production and upstream extraction and production steps. The production of drinking water bottles [5] or the clamshell containers [6] was excluded. The weight of PLA in 1 000 bottles was 12.58 kg [5], and the weight of 1 000 clamshell containers was 30.54 kg.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [9] and the ReCiPe normalisation factors (see explanatory document).

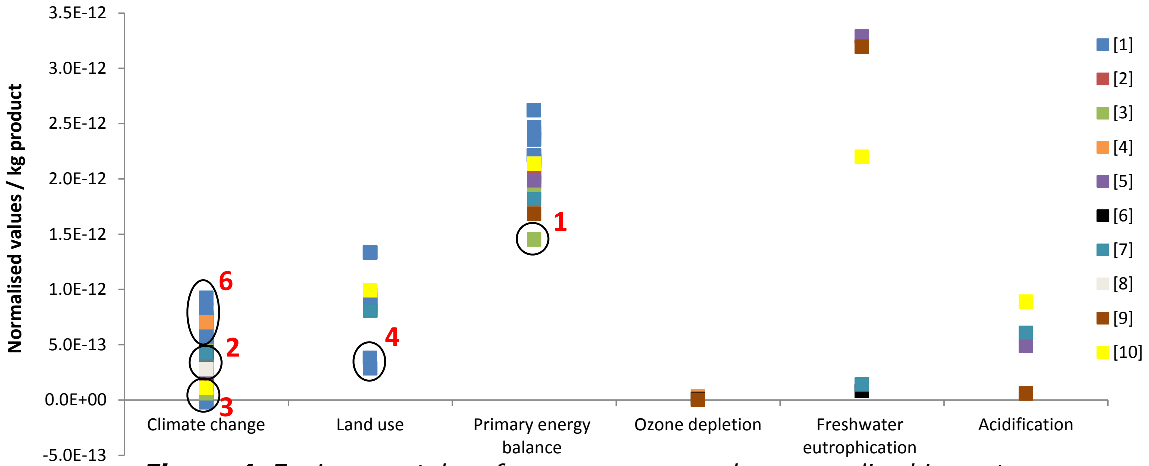


Figure 4. *Environmental performance expressed as normalised impact*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. Reference [3] presents a scenario where calcium sulphate is considered as a co-product (used in land applications), and a credit was given to the PLA system due to the avoided impacts of calcium sulphate mining. This credit reduces the primary energy demand and the climate change impacts;
2. The authors of references [8,9] considered the avoided emissions of CO_2 as a credit (in order to account for the carbon uptake during biomass growth), which fact explains the low climate change impact values reported for the corn system;
3. The lowest values found for climate change and non-renewable energy demand were obtained for the production of PLA from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [1] for the energy surplus generated from bagasse burn;
4. The land requirements for PLA production using corn stover are lower than those for corn and sugar cane. This is due to the economic allocation applied [1], which assigns a lower value to corn stover than corn kernels;
5. The authors of reference [1] account for the burning of lignin-rich waste (obtained in the pre-treatment of corn stover by hydrolyses - see bioalcohols via fermentation factsheet) to produce power and heat. This results in reduced impacts on non-renewable energy demand and climate change;
6. The highest values found for climate change impact were obtained from studies that considered cradle-to-grave boundaries, which means that the use and end-of-life phases are environmentally significant.

REFERENCES / FURTHER INFORMATION

[1] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources.
[2] Vink et al., 2003. Polym Degrad Stabil 80: 403–419.
[3] Vink et al., 2007. Industrial Biotechnology 6: 58-81.
[4] Hottle et al., 2013. Polym Degrad Stabil 98: 1898-1907.
[5] Gironi and Piemonte, 2011. Environ Prog & Sustainable Energy 30: 459-468.
[6] Madival et al., 2009. J Clean Prod 17: 1183–1194.
[7] Detzel, A., Krüger, M. Life Cycle Assessment of Polylactide (PLA) A comparison of food packaging made from NatureWorks® PLA and alternative materials, IFEU GmbH, Heidelberg, July 2006.
[8] Groot and Borén, 2010. The International J Life Cycle Assessment 15: 970-984.
[9] Vink et al., 2010. Industrial Biotechnology 3: 212-224.
[10] Vink et al., 2015. Industrial Biotechnology 3: 167-180.
[11] Benini et al., Normalisation method and data for Environmental Footprints, JRC Technical Report, Draft v.2014.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC

ENVIRONMENTAL FACTSHEET: *Polyhydroxyalkanoates*

PRODUCT INFORMATION

Polyhydroxyalkanoates (PHAs) are biobased, biodegradable and biocompatible polymers. To date, there are 150 different known monomer compositions for PHAs (such as: polyhydroxybutyrate PHB and polyhydroxyvalerate PHV), which have a high variety of properties and applications. PHAs can replace currently used petrochemical polymers in coatings and packaging. Owing to their biocompatibility and biodegradability, PHAs can also be used for medical purposes.

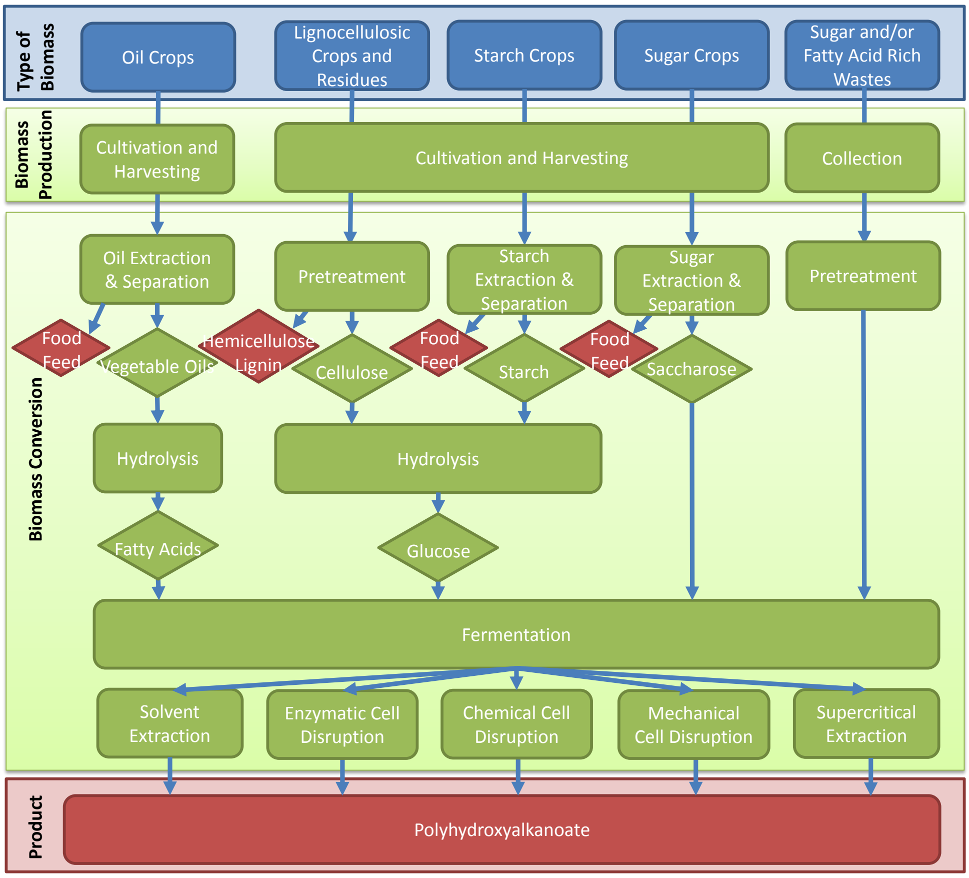


Figure 1. *PHA production chains*

PHAs can be produced via the fermentation of sugars, fatty acids and waste products (see Figure 1). Different types of microorganisms can synthesise PHAs. These polymers are accumulated as intracellular granules during nutrient depletion phases or during an abrupt increase in carbon supply. They are normally produced in two steps (a growth step and a polymer accumulation step). The type of microorganisms used and the operation conditions influence the molecular weight of PHAs, which may range from 2×10^5 to 3×10^6 Da [1]. Most commercially produced PHAs are synthesised by pure bacterial cultures using simple carbon sources (such as sugars and fatty acids).

However, the costs of producing PHAs are high (€2.5-5/kg [2]). Research is therefore targeting the development of production processes that use: (1) less expensive raw materials (such as waste products or unrefined materials), (2) mixed bacterial cultures and (3) novel solutions to obtain higher yields. After fermentation, the microbial biomass is separated from the fermentation broth and the synthesised polymer must be extracted from inside the cells. This extraction is typically made using organic solvents (e.g. ethanol, acetone, chloroform). The large quantities of solvents needed for the extraction reduce the environmental performance and increase the costs of PHA production. Various alternatives are being studied to alleviate or avoid the setbacks of solvent extraction, such as: (1) supercritical fluids, where supercritical CO_2 acts as solvent at high pressures; (2) disruption of cell materials to release PHAs, using enzymatic, chemical or mechanical (high-pressure homogenisation, ultrasonic disruption and bead mills) procedures. Other methods that are being developed to facilitate PHA extraction/separation include: (1) dissolved air floatation to separate PHAs from the other components of the enzymatic cell disruption; (2) the use of genetically modified microorganisms that release PHAs more easily.

PHAs can also be produced in the plant cells of plants such as switchgrass. After cultivation and harvesting, switchgrass needs to be dried before the PHAs can be extracted from the plant tissues.

The maturity of various PHA production technologies is summarised in Figure 2. The lignocellulosic pathway appears to be the least advanced production system, while production pathways that use sugars from sugar/starch crops or fatty acids from oil crops are already commercially available.

Technology Readiness Levels

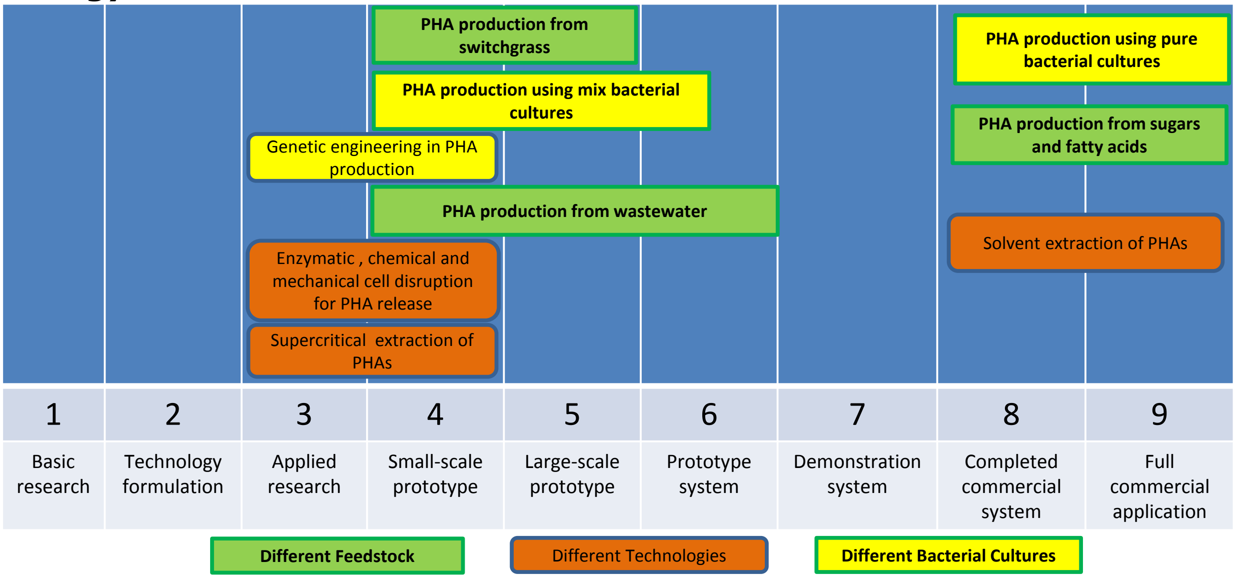


Figure 2. *Technology readiness levels for PHA production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. PHAs are biodegradable and biocompatible polymers with similar properties to the commonly used fossil-based polymers. **S2.** Due to their low permeability to oxygen, PHA polymers are suitable for food packaging.	**W1.** PHA production costs are higher than those of fossil polymers.
O1. The use of PHAs has been approved for both food contact material and surgical sutures. **O2.** The new developments in PHA extraction and yields, and use of wastes could decrease PHA production costs.	**T1.** Biomass availability for the production of PHAs due to competition with other uses. **T2.** Cost of raw material.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of PHAs summarised in Table 1 is based on the available relevant LCA data for different materials: corn, sugar cane, lignocellulosic wastes (a less mature technology, but with potential for improvement) and oil crops. Most of the values presented refer to the cradle-to-gate (see Figure 3) LCA approach.

The most widely reported impact categories are climate change, land use, primary energy and non-renewable energy. Few or no results were found for the other impact categories of the environmental sustainability assessment methodology developed in the context of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment

1. Cradle to gate: includes the resource extraction (energy, materials and water), transport and the production steps up to the exit gate of the PHA factory. **2. Cradle to grave:** in addition to the cradle-to-gate activities, this system includes the transport and distribution of the product, the use of PHAs and their end-of-life stage.

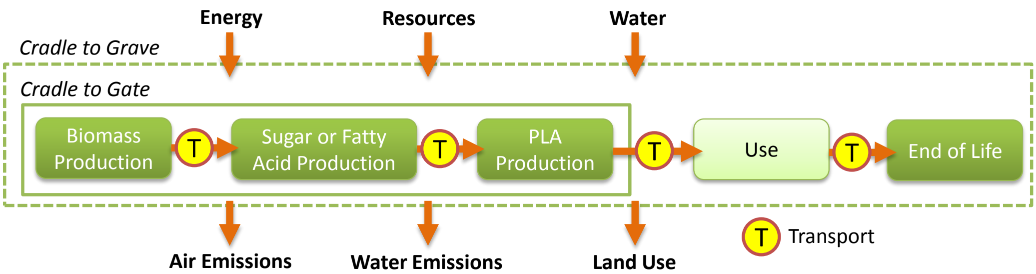


Figure 3. *LCA system boundaries for PHA production and end-of-life stage*

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of PHA in a cradle to gate system

Raw material input	Corn	Sugar Cane	Lignocellulosic wastes	Soybean	Rapeseed
Allocation/substitution	A($-m), S	A($), S	A($-m), S	m	A($), S
Geographical coverage	US, Europe	South Africa, Brazil	US, Europe	US	Europe
References	[3,6,7,8,9]	[3,5]	[3,4,6,8]	[9]	[3]
Impact categories from Environmental Sustainability Assessment methodology					
Climate change (kg CO_2-eq.)	(-2.3-0.45)1 (3.0-4.2)	(0.1-1.1)1,3	(1.3-5.1)	0.261	(5-6.9)5
Ozone depletion (kg CFC-11-eq.)	N.A.	$1.7E^{-7}$ [5]	N.A.	N.A.	N.A.
Acidification (mol H^+-eq.)	2.14 [6]	N.A.	0.81 [6]	N.A.	N.A.
Marine water eutrophication (kg N-eq.)	$1.9E^{-3}$ [6]	N.A.	$1.9E^{-3}$ [6]	N.A.	N.A.
Freshwater eutrophication (kg PO_4-eq.)	N.A.	$5.2E^{-3}$ [5]	$5.4E^{-4}$-$5.0E^{-3}$ [4]	N.A.	N.A.
Additional impact categories					
Fresh water ecotoxicity (kg 1,4-DB-eq.)	N.A.	0.106 [5]	N.A.	N.A.	N.A.
Human Toxicity - non cancer effects (kg 1,4-DB-eq.)	N.A.	0.86 [5]	N.A.	N.A.	N.A.
Photochemical ozone formation (kg C_2H_4-eq.)	N.A.	$7.8E^{-4}$ [5]	$3.1E^{-3}$-$4.9E^{-3}$ [4]	N.A.	N.A.
Land use (m^2)	(3.8-4.0) [3]	(4.0-4.1) [3]	(1.6-1.7)6 [3]	N.A.	(11.4-18.8)5
Terrestrial ecotoxicity (kg 1,4-DB-eq.)	N.A.	$9.0E^{-3}$ [5]	N.A.	N.A.	N.A.
Marine ecotoxicity (kg 1,4-DB-eq.)	N.A.	1290 [5]	N.A.	N.A.	N.A.
Acidification (kg SO_2-eq.)	N.A.	$2.5E^{-2}$ [5]	$1.6E^{-2}$-$2.8E^{-2}$ [4]	N.A.	N.A.
Abiotic depletion (kg Sb-eq.)	N.A.	$2.2E^{-2}$ [5]	N.A	N.A.	N.A.
Primary energy (MJ)	(144.2-161.0) [3]	(161.0-183.8) [3]	(148.4-170.7)[3]	N.A.	(164.1-171.5)
Non-renewable energy (MJ)	(2.5)2 (69.0-111.6)4	(33.4-59.0)3	(61.6-78.2)4	50	(60.9-109)

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [10] and the ReCiPe normalisation factors (see explanatory document).

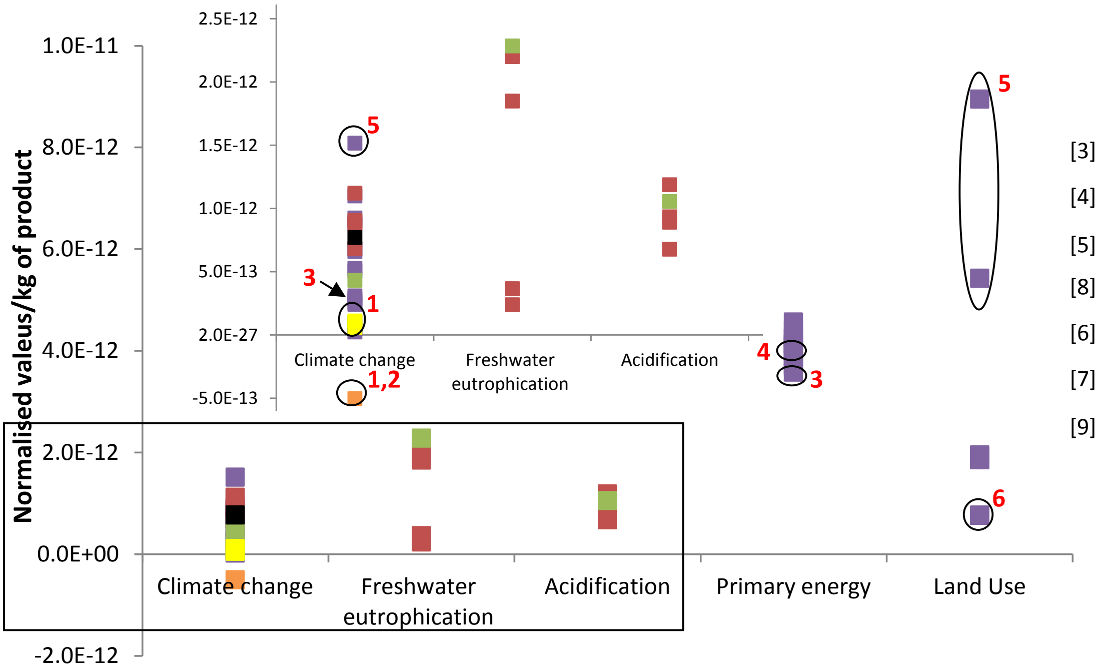


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table1 and Figure 4):

1. The authors of references [7,8,9] considered the avoided emissions of CO_2 as a credit (to account for the carbon uptake during biomass growth), which explains the low climate change impact values;
2. In addition, the authors of reference [7] considered the burning of corn stover and fermentation residues to generate electricity and steam, which explains the low consumption of non-renewable energy and also lower climate change impacts. When this is not considered, the non-renewable energy results can increase up to 111.6 $MJ/kg_{polymer}$;
3. The lowest values found for climate change and non-renewable energy demand were obtained for the production of PHAs from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [3] for the energy surplus, generated from bagasse burn;
4. The authors of reference [3] account for the burning of lignin-rich waste [obtained during the pre-treatment of corn stover using hydrolysis - see bioalcohols via fermentation factsheet) to produce power and heat. This results in reduced impacts on non-renewable energy demand and climate change;
5. Higher climate change and land use impacts were found for the rapeseed pathway due to its lower productivity levels;
6. Land requirements for PHA production based on corn stover are lower compared with those based on corn, sugar cane and rapeseed. This is due to the economic allocation applied (used for dividing the impacts between two products) [3], which assigns a lower value to corn stover than corn kernels.

REFERENCES / FURTHER INFORMATION

[1] Akaraonye et al., 2010. J Chem Technol Biotechnol, 85: 732-743.
[2] Chanprateep, 2010. J Biosc Bioeng, 110: 621-632.
[3] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/
[4] Kendall, 2012. Resour Conserv Recy, 61: 69-74.
[5] Harding et al., 2007. J Biotechnol 130: 57-66.
[6] Kim and Dale, 2005. Biopolymers, 10: 200-210.
[7] Kim and Dale, 2008. Environ Sci Technol, 42: 7690-7695.
[8] Yu and Chen, 2008. Environ Sci Technol, 42: 6961-6966.
[9] Akiyama et al., 2003. Polym Degrad Stabil 80: 183-194.
[10] EC–JRC, 2014.Normalisation method and data for environmental footprint–Final – EUR 26842 EN.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
ANIMPOL
BIO-TIC

ENVIRONMENTAL FACTSHEET: ***Acetic Acid***

PRODUCT INFORMATION

Acetic acid (CH_3COOH) is a carboxylic acid with applications in both chemical and food industries. It is largely used in the production of vinyl acetate (a monomer used in the manufacture of the polymer polyvinyl acetate) and other esters (commonly used in inks and paints), and as a solvent in different chemical reactions and purification processes.

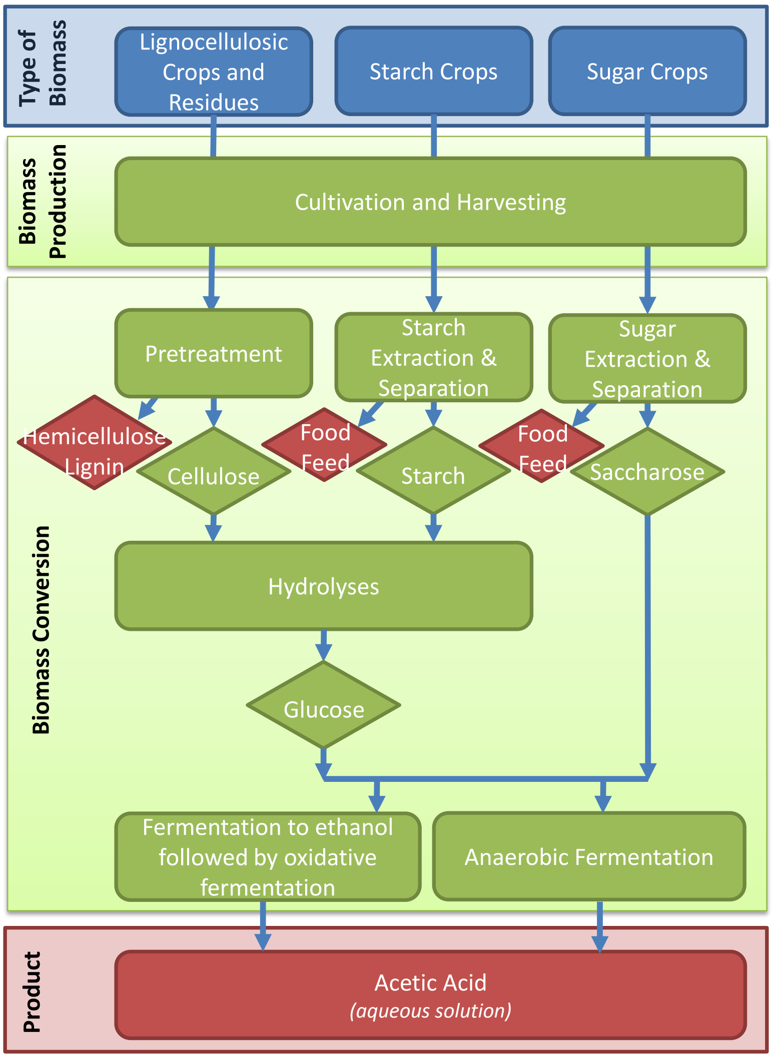


Figure 1. *Acetic acid production chains*

Worldwide, acetic acid is mainly produced from fossil-based resources through the carbonylation of methanol. It can also be commercially produced through the fermentation (bio-based pathway) of sugars and ethanol, mostly for food purposes, e.g. for the production of vinegars (aqueous solutions of acetic acid, up to 15%). Acetic acid can be produced by two fermentation processes: i) oxidative (aerobic) fermentation of ethanol and ii) anaerobic fermentation of sugars.

Oxidative fermentation requires a first step of sugar fermentation to produce ethanol (by yeasts), followed by ethanol fermentation to produce acetic acid, which is accomplished by bacteria of the genus *Acetobacter*, performed under oxygen supply.

Anaerobic fermentation occurs without oxygen using anaerobic bacteria (such as *Clostridium thermoaceticum*) that can directly convert sugars into acetic acid. The rate of production of these bio-based pathways is low due to the inhibition of bacteria at low pHs (higher levels of acidity). Therefore, research is focused on improving acetic acid productivity by developing bacterial strains with improved pH tolerance. Due to the low concentrations of acetic acid in the final fermentation broth, it is difficult to separate/purify since the conventional separation methods (such as distillation) are not economically viable at these low concentrations.

Processes such as electrodialysis, pervaporation and solvent extraction (liquid-liquid extraction) have been proposed to remove acetic acid from the fermentation broths.

The maturity of various acetic acid production technologies is summarised in Figure 2. The use of lignocellulosic materials appears as the least advanced production system, while the use of sugars from starch or sugar crops is commercially available for the production of acetic acid aqueous solutions.

Technology Readiness Levels

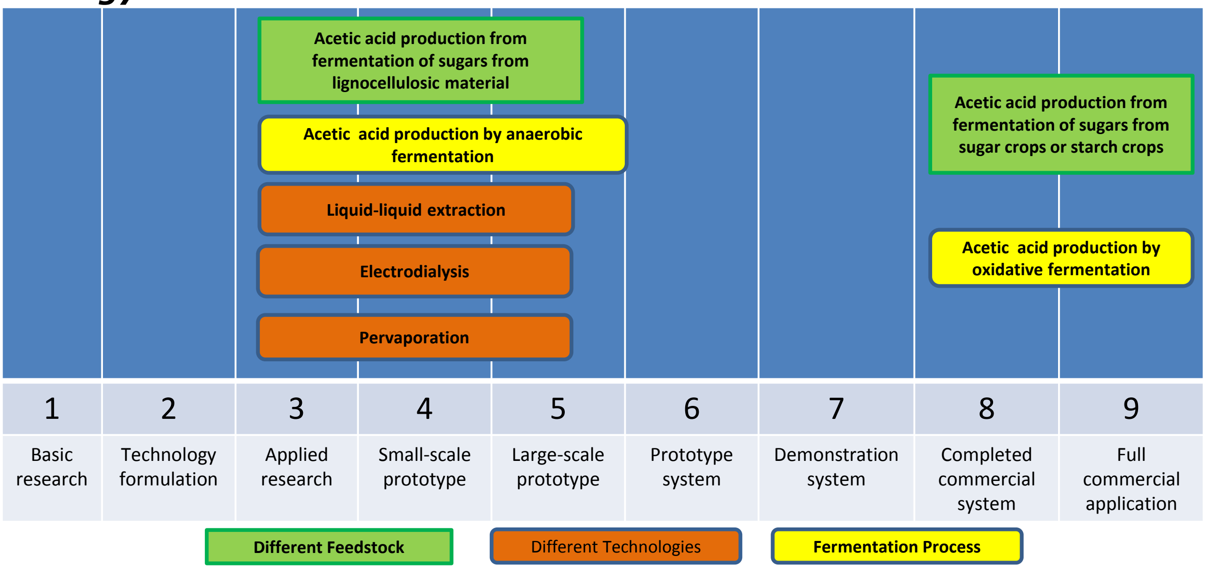


Figure 2. *Technology readiness levels for acetic acid production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. Acetic acid has a wide variety of applications in food and chemical industries.	**W1.** The bio-based pathway has low productivities. **W2.** It is difficult to separate acetic acid from the fermentation broth.
O1. The development of new separation technologies may increase the production efficiency. **O2.** The development of bacterial strains with higher pH tolerance may improve acetic acid yields.	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of acetic acid summarised in Table 1 is based on the available relevant LCA data for acetic acid production through anaerobic fermentation using different raw materials (corn, sugar cane and corn stover) and purification methods such as liquid-liquid extraction, distillation and electrodialysis.

Most of the values reported in the literature were calculated using cradle-to-gate (see Figure 3) LCA approach. Climate change results are also found for cradle-to-grave systems that consider incineration without energy recovery as an end-of-life scenario for acetic acid [1]. The BREW project [1] considers the use phase to be negligible in cradle–to-grave calculations.

The most widely reported impact categories are climate change, land use, primary energy and non-renewable energy. No results were found for the remaining impact categories described in the environmental sustainability assessment methodology that was developed in the context of this assessment (see explanatory document).

System boundaries of the environmental assessment

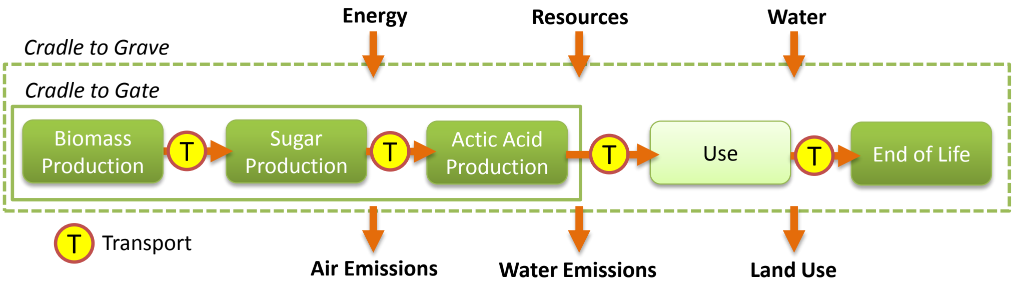


Figure 3. *LCA system boundaries for acetic acid production and end-of-life stage*

1. Cradle to gate: includes resource extraction (energy, materials and water), transport and the production steps until the exit gate of the acetic acid factory. **2. Cradle to grave:** in addition to the cradle-to-gate activities, this system includes transport and distribution of the product, use of acetic acid and its end-of-life stage.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of acetic acid in a cradle-to-gate system

Raw material input	Corn		Sugar cane		Corn stover	
LCA boundaries	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave
Allocation/substitution	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S
Geographical coverage	EU	EU	Brazil	Brazil	EU	EU
References	[1]	[1]	[1]	[1]	[1]	[1]
Impact categories from Environmental Sustainability Assessment methodology						
Climate change ($kg\ CO_2$-eq.)	(0.7-6.6)	(2.1-8.1)***1***	(-0.1-4.7)***2***	(1.1-6.2)***1***	(0.0-5.5)***3***	(1.5-7.0) ***1***
Additional impact categories						
Land use (m^2)	(1.4-2.6)	N.A.	(1.5-2.6)	N.A.	(0.6-1.1)***4***	N.A.
Primary energy (MJ)	(63.4-180.7)	N.A.	(69.6-191.9)	N.A.	(64.9-183.5)	N.A.
Non-renewable energy (MJ)	(43.7-144.9)	N.A.	(22.5-106.3)***2***	N.A.	(31.9-123.4)***3***	N.A.

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [2] and the ReCiPe normalisation factors (see explanatory document).

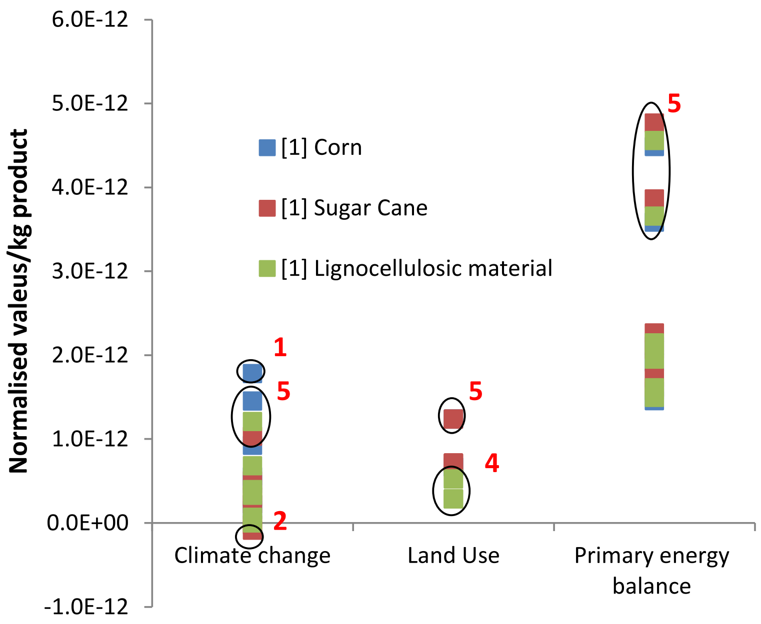


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. The highest impact values found for climate change were reported from studies that consider cradle-to-grave boundaries. It can be therefore concluded that the use and the end-of-life phases are environmentally significant;
2. The lowest values found for climate change and non-renewable energy demand were obtained for the production of acetic acid from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [1] for the energy surplus, generated from bagasse burn;
3. The BREW project [1] considers burning of lignin-rich waste (obtained in the pre-treatment of corn stover using hydrolysis - see bioalcohols via fermentation factsheet) to produce power and heat. This results in reduced impacts on non-renewable energy demand and climate change;
4. Less land is required to produce acetic acid from corn stover than from corn and sugar cane. This is due to the fact that economic allocation is applied (used for dividing the impacts between two products) [1], which assigns a lower economic value to corn stover than to corn kernels;
5. The highest values found for all the reported impacts correspond to cases where batch anaerobic fermentation is used to produce acetic acid, as opposed to the use of continuous fermentation. This indicates that the use of continuous operation systems is likely to reduce the environmental impact of acetic acid production.

REFERENCES / FURTHER INFORMATION

[1] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/

[2] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC

ENVIRONMENTAL FACTSHEET: ***Succinic Acid***

PRODUCT INFORMATION

Succinic acid ($COOH(CH_2)_2COOH$) is a carboxylic acid used in the food (as an acidulant), pharmaceutical (as an excipient), personal care (soaps) and chemical (pesticides, dyes and lacquers) industries. Bio-based succinic acid is seen as an important platform chemical for the production of biodegradable plastics and as a substitute of several chemicals (such as adipic acid) [1].

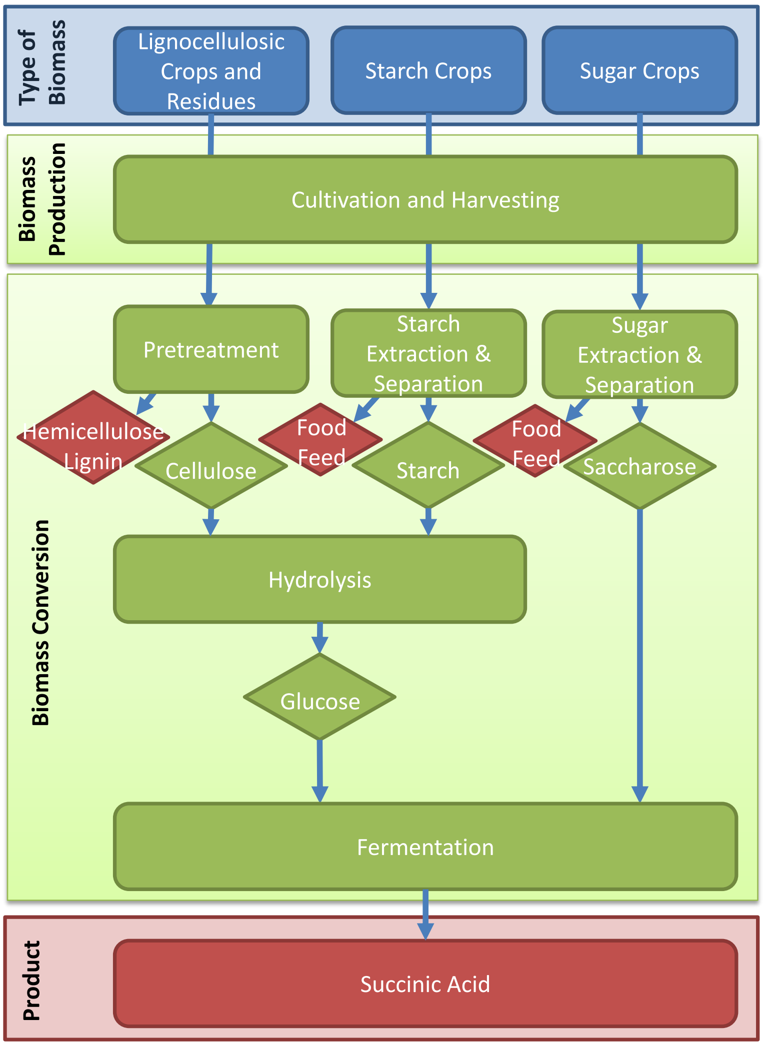


Figure 1. *Succinic acid production chains*

Succinic acid is mainly produced from fossil resources through maleic acid hydrogenation. It can also be produced through the fermentation of sugars, in which case, in addition to succinic acid, other carboxylic acids (such as lactic acid, formic acid, propionic acid) and alcohols (such as ethanol) are also obtained. The production ratios of these by-product compounds depend on the microorganism strain used and on the operation conditions. Several companies and industrial consortiums started bio-based production of succinic acid at demonstration scale up to 30000 tonnes/year of full capacity per production plant [2 and European Bioplastics]. Two strategies are being used for succinic acid fermentation [1]: (1) Use of bacteria strains, isolated from rumen, which are excellent natural succinic acid producers whose yields can be improved though metabolic engineering; (2) Use of well-known industrial microorganisms (such as *Escherichia coli* or *Saccharomyces cervisiae*), whose minor succinic acid production capability is modified to produce high yields through metabolic engineering.

Succinic acid can be produced through the fermentation of sugars from different types of biomass, such as starch or sugar crops and lignocellulosic materials. Some reports also suggest the use of glycerol as a carbon source that can be fermented into succinic acid. The maturity of various acetic acid production technologies is summarised in Figure 2. The production of carboxylic acids by fermentation typically requires neutralisation of the fermentation broth to prevent inhibition of the microorganisms by low pH levels (see lactic acid and acetic acid fact sheets). This process yields carboxylic salt (usually calcium succinate), which has to be acidified to obtain the acid component (succinic acid). These neutralisation and acidification processes can result in high costs and poor environmental performance due to the use of large quantities of base and acid, and the generation of vast amounts of effluents e.g. calcium sulphate salts residues generated in the acidification process. Current technological developments are therefore focused on increasing the yield of succinic acid using low pH fermentation strains and on increasing the efficiency of the separation and purification steps (the latter usually accomplished by crystallisation). The separation of succinic acid from the fermentation broth should overcome several challenges such as low succinic acid concentration and its separation from other carboxylic acids (fermentation by-products). Several separation technologies have been proposed: liquid-liquid extraction, adsorption, electrodialysis, precipitation and crystallisation.

Technology Readiness Levels

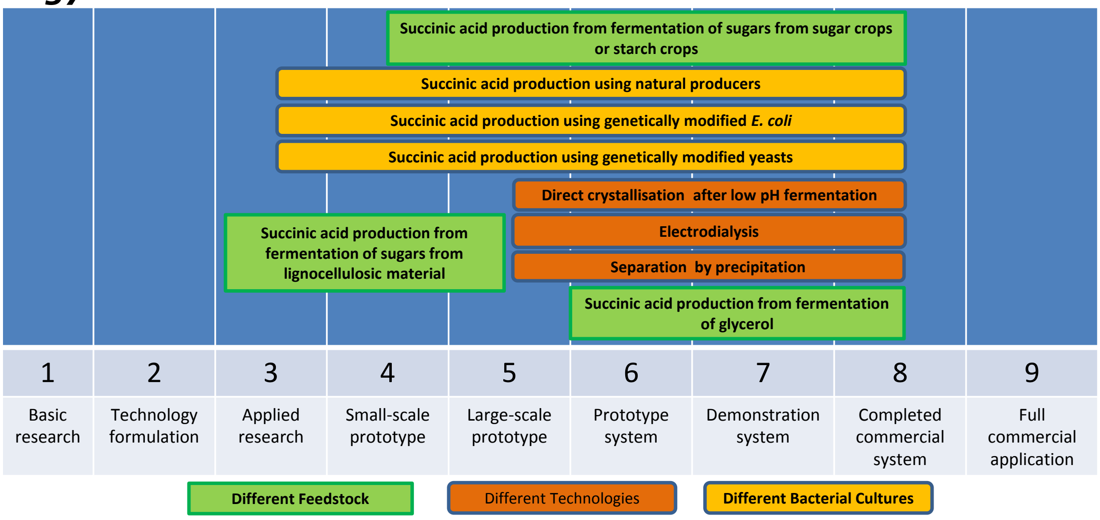


Figure 2. *Technology readiness levels for succinic acid production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. Bio-based succinic acid can replace different fossil-based chemicals in various applications. **S2.** Succinic acid can be converted into numerous chemicals.	**W1.** The purification of succinic acid is complex due to simultaneous production of other carboxylic acids. **W2.** Today the world market for succinic acid is relatively small. [2]
O1. Several industrial consortiums started producing bio-based succinic acid, with the aim of achieving full commercial application. **O2.** Succinic acid is considered as an important new platform chemical with a high market potential [1].	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of succinic acid summarised in Table 1 is based on the available relevant LCA data for succinic acid production through fermentation of sugars using different raw materials (corn, sugar cane and corn stover) and purification methods (crystallisation, electrodialysis and precipitation).

Most of the values refer to the cradle-to-gate (see Figure 3) LCA approach. Climate change results are also found for cradle-to-grave systems that consider incineration without energy recovery as an end-of-life scenario for succinic acid [3]. The BREW project [3] considers the use phase in the cradle-to-grave calculations to be negligible.

For this product, the available environmental impact results were found for climate change, land use, primary energy and non-renewable energy. No results were found for the remaining impact categories described in the environmental sustainability assessment methodology developed in the context of of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment

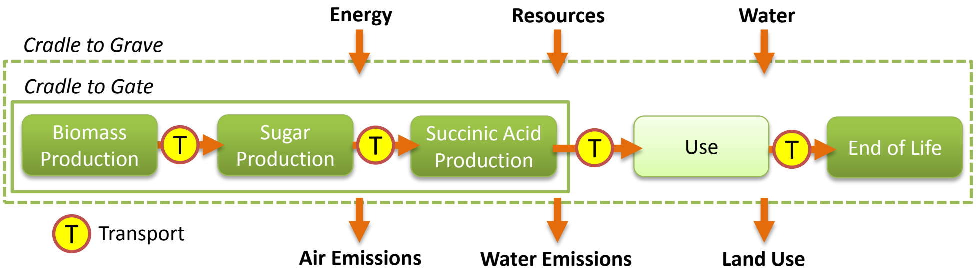


Figure 3. *LCA system boundaries for succinic acid production and end-of-life stage*

1. Cradle to gate: includes resource extraction (energy, materials and water), transport and the production steps until the exit gate of the succinic acid factory. **2. Cradle to grave:** in addition to the cradle-to-gate activities, this system includes transport and distribution of the product, use of succinic acid and its end-of-life stage.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of succinic acid

Raw material input	Corn		Sugar cane		Corn stover	
LCA boundaries	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave
Allocation/substitution	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S
Geographical coverage	EU	EU	Brazil	Brazil	EU	EU
References	[2,3]	[3]	[3]	[3]	[3]	[3]
Impact categories from Environmental Sustainability Assessment methodology						
Climate change ($kg\ CO_2$-eq.)	(0.3-3.1)	(1.8-4.6)***1***	(-0.4-2.1)***2***	(0.9-3.5) ***1***	(-0.2-2.5)***3***	(1.2-4.0) ***1***
Additional impact categories						
Land use (m^2)	(1.5-2.6) [3]	N.A.	(1.5-2.6)	N.A.	(0.8-1.7)***4***	N.A
Primary energy (MJ)	(48.7-102.6) [3]	N.A.	(54.2-108.9)	N.A.	(50.1-104.2)	N.A.
Non-renewable energy (MJ)	(28.0-66.5)	N.A.	(9.1-44.9)***2***	N.A.	(15.0-54.5)***3***	N.A.

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System Expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [4] and the ReCiPe normalisation factors (see explanatory document).

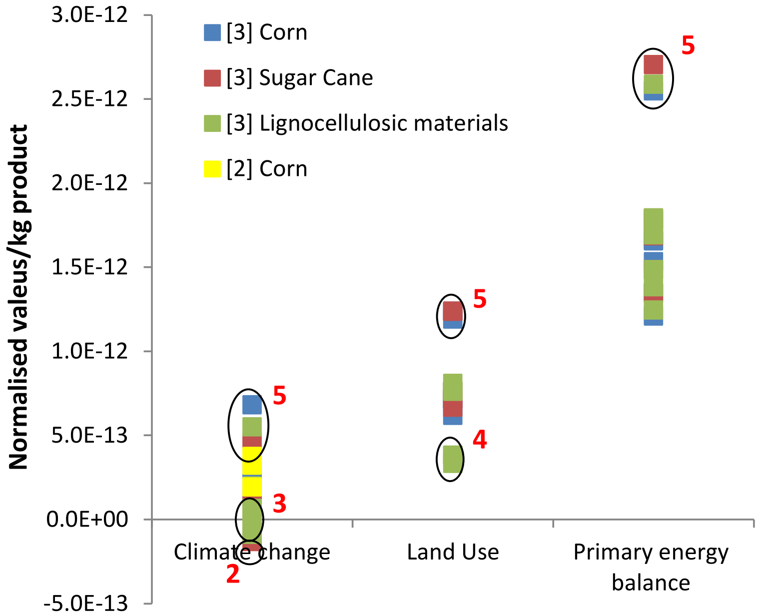


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4)

1. The highest values found for climate change were obtained from studies that consider cradle-to-grave boundaries. It can therefore be concluded that the use and the end-of-life phases can lead to significant environmental impacts;
2. The lowest values found for climate change and non-renewable energy demand were obtained for the production of succinic acid from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [3] for the energy surplus, generated from bagasse burn;
3. Reference [3] considers the burning of lignin-rich waste (obtained in the pre-treatment of corn stover by hydrolysis - see bioalcohols via fermentation factsheet) to produce power and heat. This results in lower impacts on non-renewable energy demand and climate change;
4. The land requirements for succinic acid production from corn stover are lower than those from corn and sugar cane. This is due to applied economic allocation (used for dividing the impacts between two products) [3], which assigns a lower value to corn stover compared to the corn kernels;
5. The highest impact values found for primary energy demand, land use and climate change corresponded to cases where succinic acid was produced using batch fermentation as opposed to continuous fermentation. This indicates that the use of continuous operation systems is likely to reduce the environmental impact of succinic acid production.
6. The authors in reference [2] reported lower climate change and non-renewable energy impacts for succinic acid produced using low pH yeast fermentation with direct crystallisation when compared to the use of near neutral pH fermentation.

REFERENCES / FURTHER INFORMATION

[1] Jansen et al., 2014. Current Opinion in Biotechnology 30:190–197.
[2] Cok et al., 2014. Biofuels, Bioprod Bioref, 8: 16-29.
[3] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/
[4] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

FP7 Project REFERENCES in CORDIS www.cordis.europa.eu
BIO-TIC
SUCCIPACK
BIOREFINE-2G

ENVIRONMENTAL FACTSHEET: **Adipic Acid**

PRODUCT INFORMATION

Adipic acid is a carboxylic acid $COOH(CH_2)_4COOH$ manufactured in high volumes mostly for the production of nylon-6,6 fibres. It is also used in the production of polyurethanes, resins, plasticisers, adhesives, lubricants and in food and pharmaceutical industries.

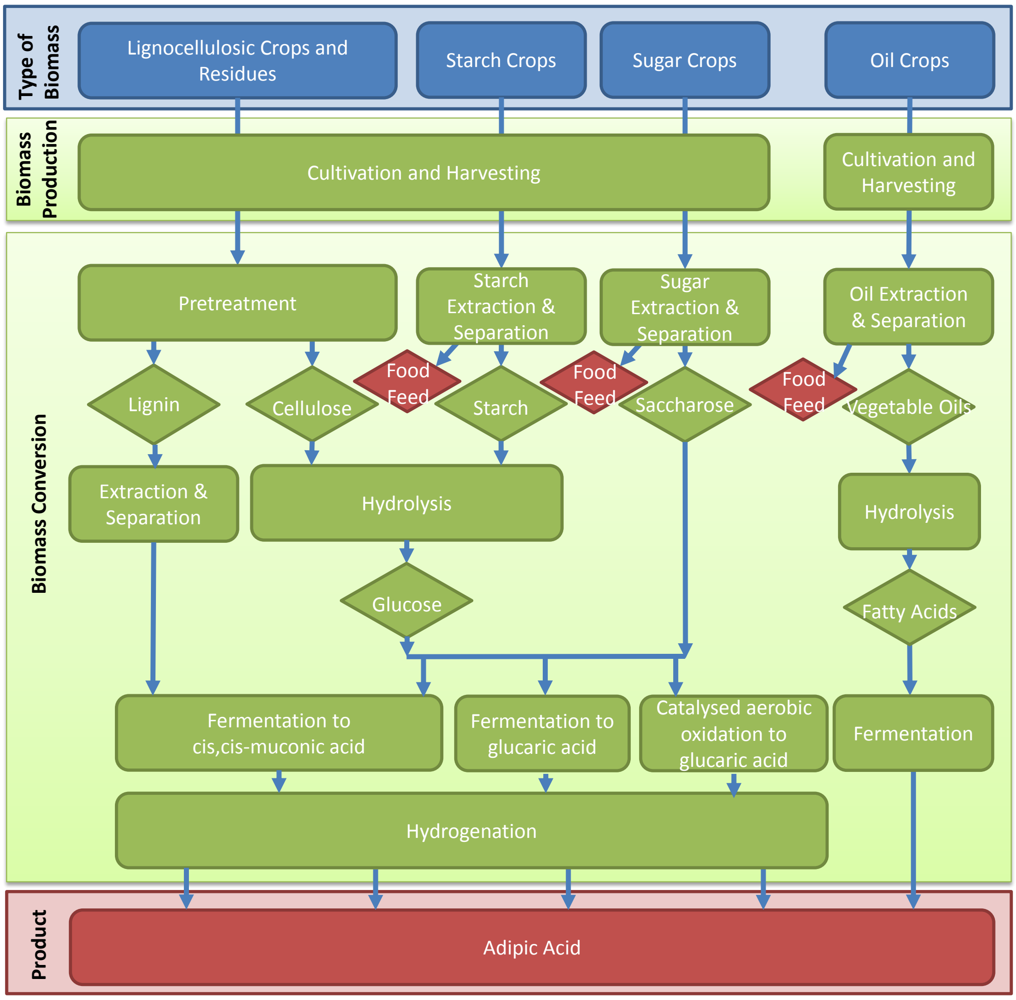


Figure 1. *Adipic acid production chains*

Most of the adipic acid commercialised today is obtained by catalytic oxidation of a cyclohexanone and cyclohexanol mixture (using nitric acid as a catalyst), both of which are obtained from benzene. This reaction also yields nitrous oxide (N_2O) [1,2], which represents an environmental concern, since N_2O has a global warming potential (GWP) that is 298 times higher than CO_2.

Adipic acid can also be obtained from bio-based materials using chemical and/or biological processes. The maturity of various bio-based adipic acid production technologies is summarised in Figure 2. Currently, there are two bio-based conversion pathways for adipic acid, which are approaching commercial production scale: (1) yeast fermentation of fatty acids from vegetable oils (biological process), and (2) catalysed aerobic oxidation of glucose to the intermediate glucaric acid followed by hydrogenation to adipic acid (chemical process).

Other alternative bio-based pathways that combine fermentation (biological process) and hydrogenation (chemical process) have also been proposed and are under development, such as: (1) fermentation of glucose to cis,cis-muconic acid and subsequent hydrogenation to adipic acid; (2) fermentation of glucose to glucaric acid and subsequent hydrogenation to adipic acid; (3) fermentation of small aromatic compounds (that can be extracted from lignin) to cis,cis-muconic acid and subsequent hydrogenation to adipic acid. The last pathway has been studied using benzoate as model substrate and has shown high conversion yields [1].

In addition, a fully biological process of glucose fermentation to adipic acid was also proposed, although this requires further development of the metabolic pathways involved in the conversion process [2].

The conventional downstream processes for adipic acid recovery involve filtration and crystallisation steps in order to reach the purity level required for polymer production.

Technology Readiness Levels

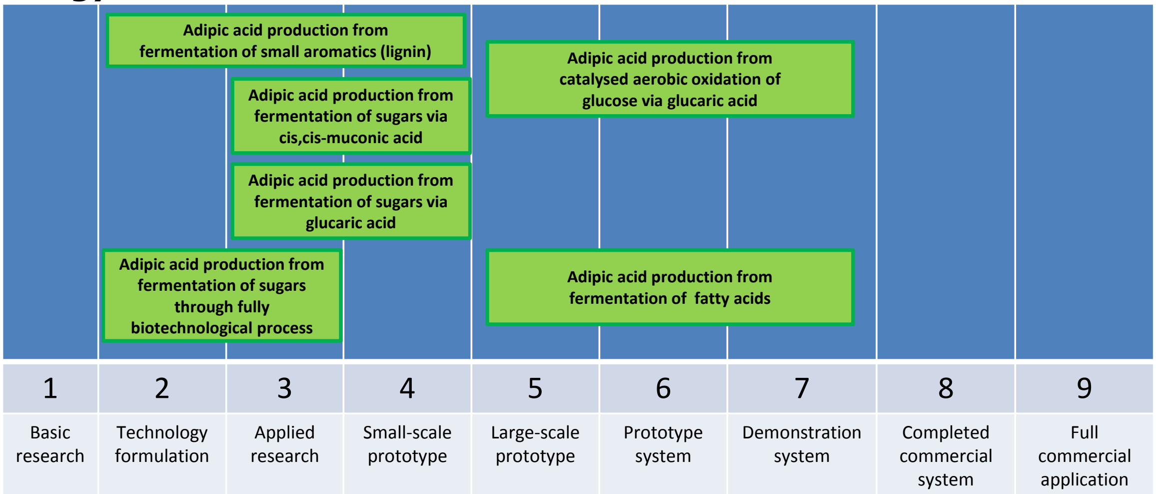


Figure 2. *Technology readiness levels for adipic acid production*

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. The bio-based adipic acid production pathway is more environmentally sound than the fossil-based one. **S2.** Adipic acid is produced in large volumes.	**W1.** The bio-based adipic-acid production pathway has not yet reached full commercial scale. **W2.** The low cost and price of fossil-based adipic acid.
O1. Two bio-based production pathways for adipic acid are about to become commercial. **O2.** The development of a fully biological conversion pathway from glucose to adipic acid may increase overall production efficiency.	**T1.** Biomass availability for the bio-based production pathway due to competition with other uses.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of adipic acid summarised in Table 1 is based on the available relevant LCA data for production through the fermentation of sugars to cis,cis-muconic acid and subsequent hydrogenation to adipic acid, using different raw materials (corn, sugar cane, corn stover) and purification methods (evaporation, crystallisation and electrodialysis).

Most of the values reported in the literature were calculated using cradle-to-gate (see Figure 3) LCA approach. Climate change results are also found for the cradle-to-grave system that considers incineration without energy recovery as the end-of-life scenario for adipic acid. The BREW project [3] considers the use phase to be negligible in cradle-to-grave calculations.

For this product, the available environmental impact results were found for climate change, land use, primary energy and non-renewable energy. Few or no results were found for the remaining impact categories described in the environmental sustainability assessment methodology developed in the context of the project "Setting up the Bioeconomy Observatory" (see explanatory document).

System boundaries of the environmental assessment

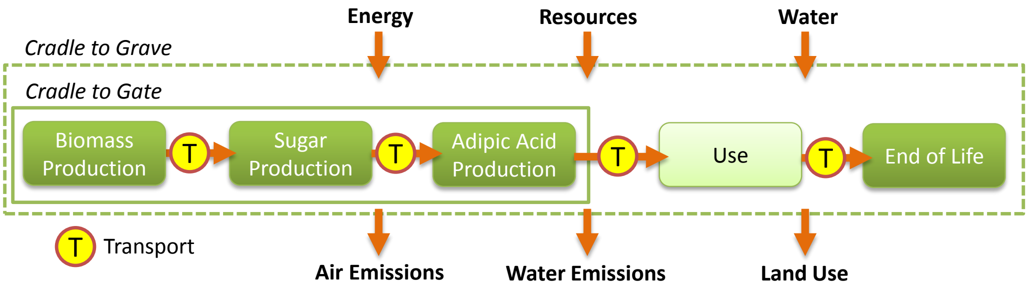


Figure 3. *LCA system boundaries for adipic acid production and end-of-life stage*

1. Cradle-to-gate: includes resource extraction (energy, materials and water), transport and the production steps until the exit gate of the adipic acid factory. **2. Cradle-to-grave:** in addition to the cradle-to-gate activities, this system includes transport and distribution of the product, the use of adipic acid, and its end-of-life stage.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of adipic acid

Raw material input	Corn		Sugar cane		Corn stover	
LCA boundaries	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to grave
Allocation/substitution	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S	A($-m), S
Geographical coverage	EU	EU	Brazil	Brazil	EU	EU
References	[3]	[3]	[3]	[3]	[3]	[3]
Impact categories from Environmental Sustainability Assessment methodology						
Climate change ($kg\ CO_2$-eq.)	(0.7-9.2)	(2.5-11.0)*1*	(-1.4-3.8)*2*	(0.5-5.6) *1*	(-0.5-6.0)*3*	(1.3-2.1) *1*
Additional impact categories						
Land use (m^2)	(2.8-7.4)	N.A.	(2.8-7.5)	N.A.	(1.1-3.0)*4*	N.A.
Primary energy (MJ)	(81.8-295.6)	N.A.	(93.7-327.3)	N.A.	(84.7-303.4)	N.A.
Non-renewable energy (MJ)	(44.3-195.4)	N.A.	(3.2-85.7)*2*	N.A.	(21.5-134.4)*3*	N.A.

N.A.: Not Available.
A: Allocation ($-economic; E-energy; m-mass).
S: Substitution.
SE: System Expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [4] and the ReCiPe normalisation factors (see explanatory document).

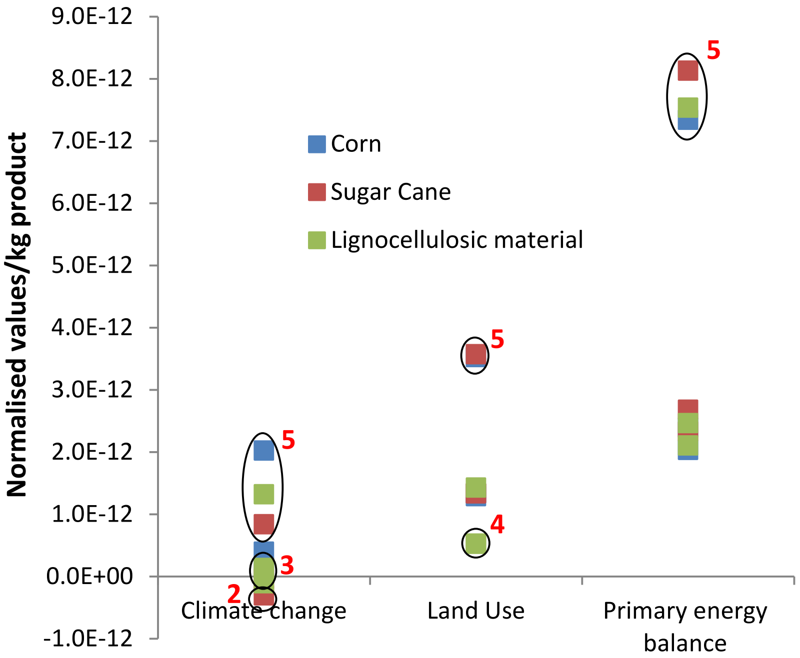


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. The highest impact values found for climate change were obtained from studies that consider cradle-to-grave boundaries. It can be therefore concluded that the use and the end-of-life phases can lead to significant environmental impacts; values
2. The lowest values found for climate change and non-renewable energy demand were obtained for the production of adipic acid from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [3] for the energy surplus, generated from bagasse burn;
3. The BREW project [3] considers burning of lignin-rich waste (obtained in the pre-treatment of corn stover using hydrolysis - see bioalcohols via fermentation factsheet) to produce power and heat. This assumption results in reduced impacts on non-renewable energy demand and climate change;
4. Less land is required to produce adipic acid from corn stover than from corn and sugar cane. This is due to the applied economic allocation (used for dividing the impacts between two products) [3], which assigns a lower economic value to corn stover than to corn kernels;
5. The highest values found for all reported impacts correspond to cases where batch fermentation is used to produce adipic acid, as opposed to the use of continuous fermentation. This finding indicates that the use of continuous operation systems is likely to reduce the environmental impact of adipic acid production.

REFERENCES / FURTHER INFORMATION

[1] van Duren et al., 2011. Biotechnology and Bioengineering, 108:1298-1306.
[2] Polen et al., 2013. Journal of Biotechnology, 167:75– 84.
[3] BREW Project - Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources. http://brew.geo.uu.nl/
[4] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

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Bioenergy Pillar

ENVIRONMENTAL FACTSHEET: ***Bioalcohols via Fermentation***

PROCESS INFORMATION

Fermentation is a **biochemical pathway** that permits the production of bioalcohols from a wide range of biomass materials. As shown in Figure 1, the main steps in the process are:

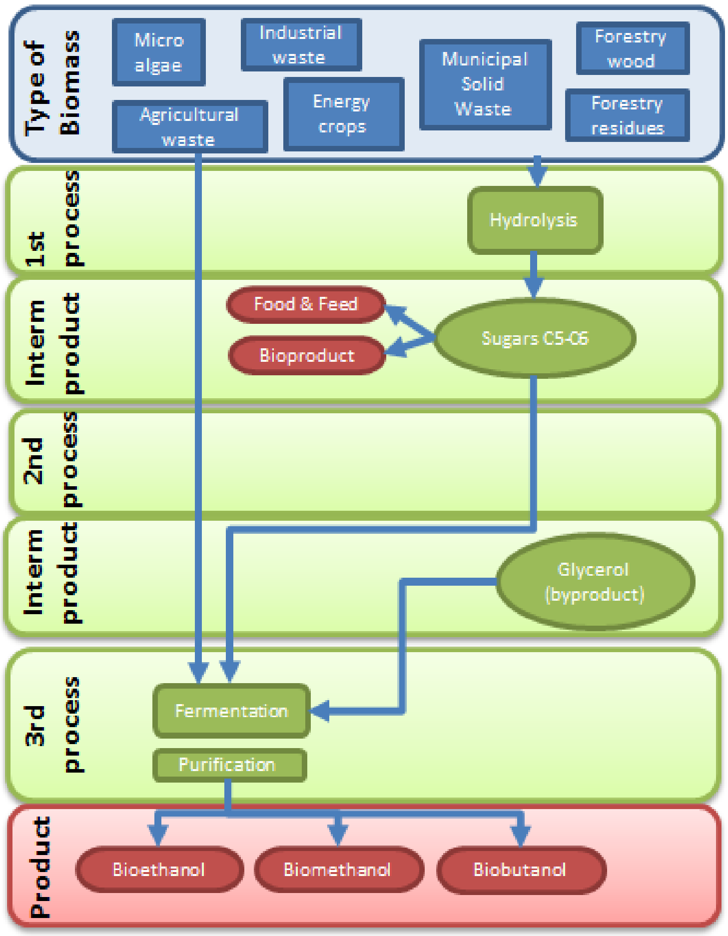


Figure 1. *Flowsheet of the fermentation process*

- During fermentation, sugars are converted (typically under anaerobic conditions) into cellular energy, producing alcohol and carbon dioxide as metabolic waste products.
- Preprocessing and hydrolysis are necessary for some materials such as lignocellulosic biomass (e.g. wood, waste from the paper industry, some energy crops) in order to convert the starch and the cellulose/hemicellulose into sugars (mainly hexose C6 and pentose C5) that can then be converted into biofuel by most microorganisms. C6 and C5 can also be used to produce certain biochemicals.
- To use this alcohol as fuel, water must be removed from the product (purification phase).
- Glycerol (by-product from the transesterification process – see the Biodiesel via transesterification factsheet) can also be fermented to produce bioalcohols.
- Other by-products of this pathway are biomass of the fermenting microorganisms used as fodder or fuel, and lignin-rich material used for direct combustion, gasification or production of value added products.

Technological overview

Hydrolysis involves hemicellulose and lignin removal and **cellulose hydrolysis**. Three different processes are used: **acid hydrolysis (diluted or concentrated)** and **enzymatic hydrolysis**. After hydrolysis, the resulting simpler compounds are fermented to produce alcohol. There are four main technologies or configurations:

- **Separate Hydrolysis and Fermentation (SHF),** in which both processes take place in a two-stage sequential configuration.
- **Simultaneous Saccharification and Fermentation (SSF),** which consolidates hydrolysis and fermentation mainly to overcome the high concentration of glucose that inhibits the hydrolysis process, and hence enhancing the yield of ethanol [1].
- **Simultaneous Saccharification and Co-Fermentation (SSCF),** same as SSF with the difference that the microorganisms are able to ferment both C6 and C5 [2].
- **Consolidated BioProcessing (CBP)**, whereby ethanol and the enzymes are produced in a single reactor by a single microorganism.

Finally, the product must be purified to produce fuel-grade ethanol. This is mainly done by azeotropic **distillation**, but other options are **pervaporation**, filtration and the use of membranes. For butanol production, the ABE (acetone-butanol-ethanol) is commonly fermented with *Clostridium*. Figure 2 provides an overview of the readiness level of all these technologies. Considering the feedstock used, technologies can be classified as first generation (1G - use "food crops" such as sugar cane, corn or wheat), and second generation (2G - use lignocellulosic biomass, agricultural residues or wastes). Both are more advanced in the production of bioethanol than of butanol. Bioalcohol production from microalgae is still in the early stages of development.

Technology Readiness Levels

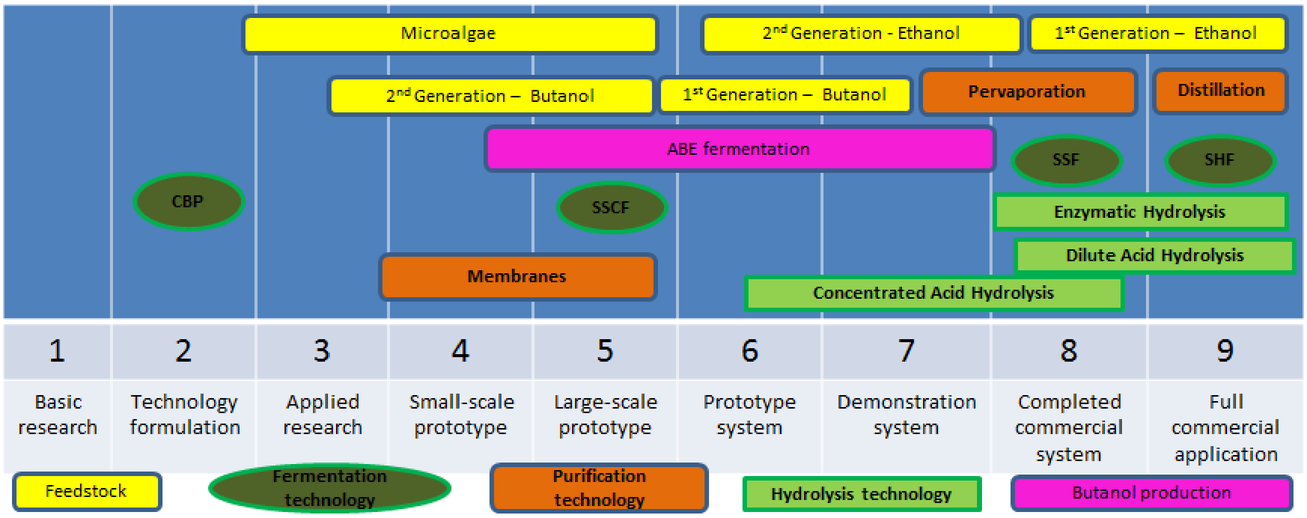


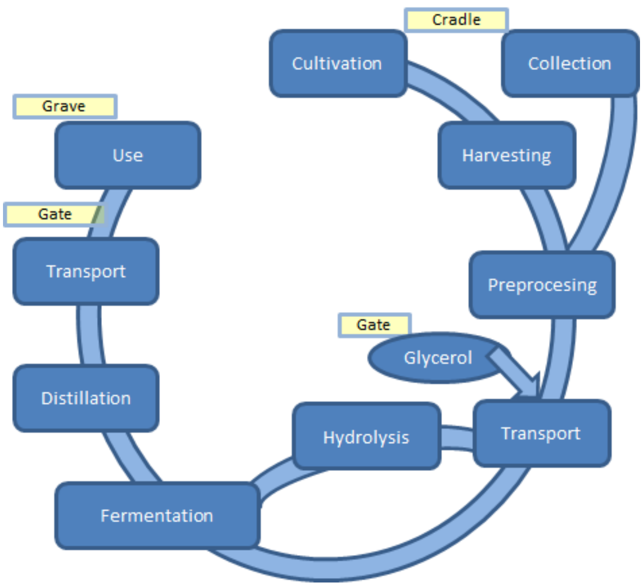
Figure 2. *Technology readiness levels for fermentation of biomass*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Well known and mature process. **S2**. Abundant and different raw materials as input. **S3**. Bioalcohols can be blended with petrol in any ratio.	**W1**. High production costs due to the low energy efficiency and the quantity of enzymes required. **W2**. Blending with petrol increases emissions of volatile organic compounds.
O1. Improved ethanol fermentation from Xylose (a major fermentable from cellulose/hemicellulose) **O2**. A fuel tax reduction or exemption on ethanol could make it cost competitive with petrol.	**T1**. Competition with food crops in land use and products. **T2**. Limited infrastructure for bioalcohol distribution

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave (Well to Wheel)**: includes cultivation (with production of ancillary products), harvesting or collection, pre-processing, transport, with or without hydrolysis, fermentation, distillation, transport to fuel tank and use in vehicles.

2. **Cradle to gate (Well to Tank)**: same boundaries as Well to Wheel, excluding the use of the fuel in the vehicle (i.e. Tank to Wheel).

3. **Gate to gate**: special case for Glycerol - includes transport of raw material, fermentation and distillation.

Figure 3: *LCA system boundaries and stages for fermentation of biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for Functional Unit (F.U.) 1 kilometre driven

Raw material input	Wheat		Sugar cane		Willow		Glycerol	Corn	
LCA boundaries	1	2	1	2	1	2	3	1	2
Allocation/substitution	A($-E), S	A($)	A($)	A($-m-E)	A(E), S	A($)	S	A($-m-E), SE	A($)
Geographical coverage	Switzerland	France	Brazil	Brazil, Argentina, Thailand	USA	Sweden	EU	USA	USA
Product	Ethanol								
References	[9]	[3]	[7]	[3,5,6]	[4]	[10]	[11]	[8]	[3]
Impact categories from Environmental Sustainability Assessment methodology									
Climate change (kg CO_2-eq.)	(-0.016 – 1.15)	0.15	(0.05-0.25)	(0.06-1.59)	(-0.032-0.072)	-9.75E-7	0.22	(-1.23-0.39)	0.11
Ozone depletion (kg CFC-11-eq.)	N.A.	N.A.	(1.5E-8-3.1E-8)	(1.94E-4-2.71E-4)	N.A.	2.98E-6	1.05E-6	(2.9E-2-2.75E-1)	N.A.
Photochemical Ozone Formation (kg NMVOC-eq.)	N.A.	2.83E-4	N.A.	2.1 E-3	N.A.	N.A.	N.A.	N.A.	2.14E-4
Fresh water eutrophication (kg P-eq.)	N.A.	1.49E-5	N.A.	(9.57E-6 – 1.35E-3)	N.A.	3.75E-5	2E-5	N.A.	3.19E-5
Marine water eutrophication (kg N-eq.)	N.A.	1.2E-3	N.A.	8.86E-4	N.A.	N.A.	N.A.	N.A.	4.25E-4
Resource depletion – water (kg)	N.A.	N.A.	N.A.	N.A.	0.931	N.A.	N.A.	N.A.	N.A.
Resource depletion – mineral (kg Sb-eq.)	N.A.	N.A.	(3E-4-1.6E-3)	(2.10-1-2.93E-1)	N.A.	1.62E-4	N.A.	(5E-4-3.05E-2)	N.A.
Additional impact categories									
Acidification (kg SO_2 eq)	N.A.	1.06E-3	(8.5E-4-1.1E-3)	(8.15E-4 – 1.13E-3)	N.A.	2.73E-4	4.36E-4	N.A.	6.38E-4
Photochemical Ozone Formation (kg C_2H_4-eq.)	N.A.	N.A.	(1.5E-4-1.6E-4)	(5.18E-4-9.85E-4)	N.A.	6.29E-5	2.18E-5	(1.6E-4-2.9E-4)	N.A.
Fresh water ecotoxicity (1,4-DB-eq.)	N.A.	N.A.	N.A.	(13.3 – 18.4)	N.A.	N.A.	N.A.	N.A.	N.A.
Terrestrial ecotoxicity (1,4-DB-eq.)	N.A.	N.A.	N.A.	(4.13 – 5.75)	N.A.	N.A.	N.A.	N.A.	N.A.
Human toxicity (1,4-DB-eq.)	N.A.	N.A.	(2E-2-7.7E-2)	1.7E-3	N.A.	N.A.	N.A.	(1.58E-4-3E-4)	N.A.
Non-renewable primary energy use (MJ)	(-1.48 – 1.81)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Cumulative Energy Demand (MJ)-non renewable	N.A.	N.A.	N.A.	N.A.	N.A.	0.36	3	N.A.	N.A.
Fossil fuel use (MJ)	N.A.	N.A.	N.A.	N.A.	-0.95	N.A.	N.A.	N.A.	N.A.
Agricultural land occupation (m^2 /year)	N.A.	0.2	N.A.	0.18	N.A.	N.A.	N.A.	N.A.	0.09
Land competition (m^2 /year)	N.A.	N.A.	N.A.	N.A.	N.A.	6.26E-4	N.A.	N.A.	N.A.

All values were transformed to the Functional Unit "power to wheels for 1 km driving a midsize car" assuming Low Heating Value of ethanol = 26.81 MJ/kg, density = 0.794 kg/l and efficiency of car = 190 MJ/100 km [12]. For glycerol: efficiency = 260 kg ethanol/t glycerol [11].

N.A: Not Available. A: Allocation ($-economic; E-energy; m-mass). S: Substitution. SE: System expansion.

The normalisation presented in Figure 4 was performed using the normalisation factors provided in the JRC methodology [13] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance:

1 The highest normalised impact values are reported for Ozone depletion and Resource depletion, mainly due to the use of fossil fuels in agriculture. Agriculture is also the main contributor to the impact values for climate change reported in reference [5].

2 Negative values for Climate change (i.e. environmental benefit) are reported in studies that use substitution (electricity produced during the process replaces the use of national grid electricity from fossil fuels [4], and Dried Distillers Grains with Solubles and wheat straw replace fuel production [9]) and that consider biogenic CO_2 emissions [10]. Reference [8] also reports negative values but in this case system expansion is used and so the system boundary and the functional unit changes to include additional products.

3 Higher impact values reported for Freshwater eutrophication [6, 8] are mainly caused by the use of agrochemicals and fertilisers in the feedstock production and the wastewater discharge from the ethanol conversion process.

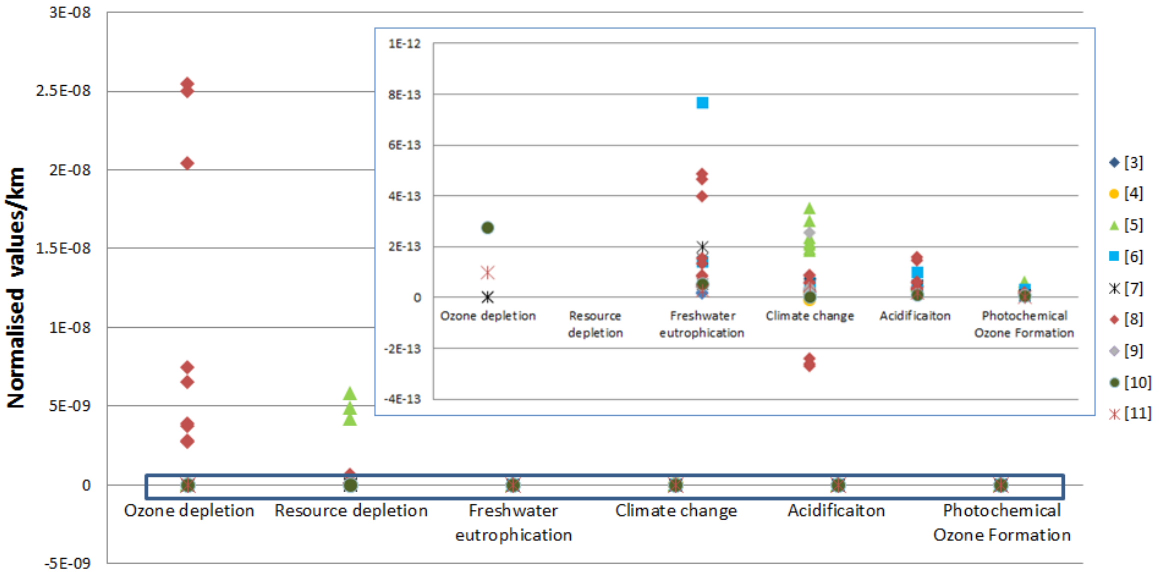


***Figure 4**: Environmental performance expressed as normalised impact categories*

REFERENCES / FURTHER INFORMATION

[1] Lin and Tanaka, 2006. Appl Microbiol Biot, 69: 627 – 642.
[2] Hamelinck et al., 2005. Biomass Bioenerg, 28: 384 – 410.
[3] Muñoz et al., 2014. Int J Life Cycle Assess, 19: 109 – 119.
[4] Budsberg et al., 2012. Forest Prod J, 62(4): 305 – 313.
[5] Amores et al., 2013. Int J Life Cycle Assess, 18: 1344 – 1357.
[6] Silalertruksa and Gheewala, 2009. Energy, 34: 1933 – 1946.
[7] Luo et al., 2009. Renew Sust Energ Rev, 13: 1613 – 1619.
[8] Luo et al., 2009. Int J Life Cycle Assess, 14: 529 – 539.
[9] Gnansounou et al., 2009. Bioresource Technol, 100: 4919 – 4930.
[10] Gonzalez-Garcia et al., 2012. Appl Energ, 95: 111 – 122.
[11] Glyfinery – FP7 Project. D-7.8 Final Report, 2012.
[12] Quirin et al., 2004. IFEU –CO_2 mitigation – Main Report.
[13] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

FP7 Project REFERENCES in CORDIS (www.cordis.europa.eu)
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ENVIRONMENTAL FACTSHEET: ***Biodiesel via Transesterification***

PROCESS INFORMATION

Transesterification (also called alcoholysis) is the reaction, normally catalysed, of a fat or oil with an alcohol to form fatty acid esters (known as Fatty Acid Methyl Esters (FAME) when the alcohol is methanol) and glycerol [1]. Figure 1 shows the main steps:

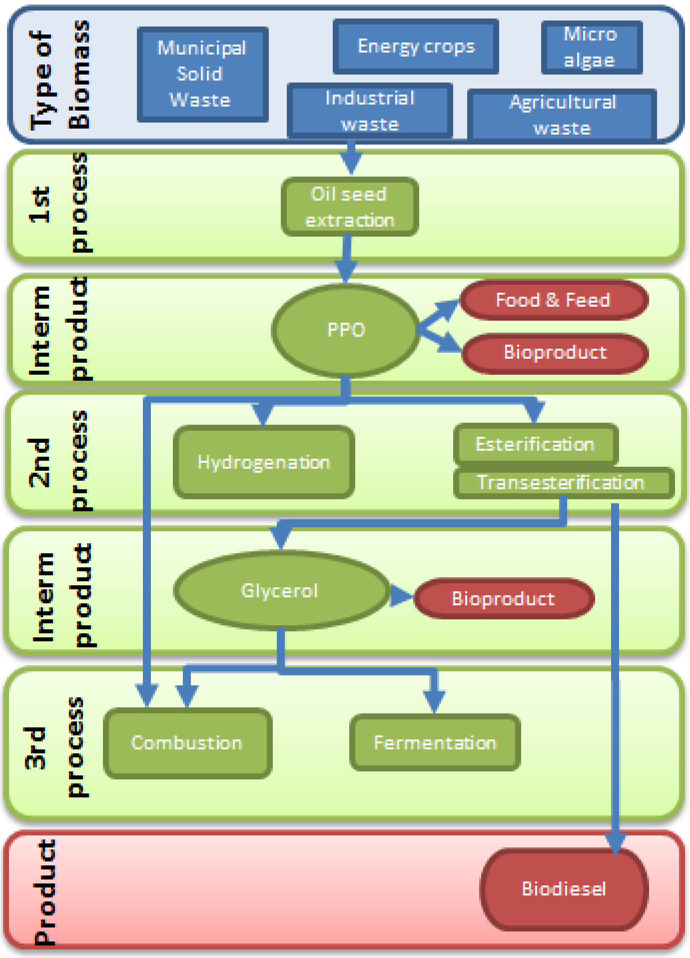


Figure 1. *Flowsheet of the transesterification process*

- The pure plant oil (PPO) is extracted from the raw material input.
- Depending on the quantity of free fatty acids (FFA) in the oil, an esterification step may be needed, usually through acid-catalysation, before the transesterification of triglycerides can take place, usually through alkali-catalysation [2]. FFAs are thereby transformed into biodiesel, thus significantly decreasing the possibility of saponification (soap making).
- The most used alcohols are methanol and ethanol because of their low cost and convenience.
- The by-product glycerol can be used (1) for energy valorisation through direct combustion, (2) for biodiesel production through fermentation (see the Bioalcohols via fermentation factsheet) or, (3) valorised as an industrial chemical (see the Glycerol factsheet) [1]. Another by-product is the pressed cake (meal) from the oilseed extraction (possible uses: feed, fertiliser or direct combustion).
- The PPO can also be valorised either via direct combustion (straight vegetable oil, SVO) (see the CHP via combustion factsheet) or be transformed into biodiesel via hydro-genation (Hydrotreated vegetable oil, HVO) (see the Biodiesel via hydrogenation factsheet).

Technological overview

The **oilseed extraction** process is usually performed at commercial scale by **solvent extraction** in conjunction with some form of **mechanical extraction**. First, the seed is crushed through a mechanical press and then a solvent is applied, recovering up to 99.5% of the oil contained in the seed. The most widely used technology is percolation using hexane as a solvent [3].

For the **esterification-transesterification** treatment (esterification pretreatment for high (more than 5-6%) FFA materials), four methods are mainly applied [1]:

- **enzymatic methods** (rather expensive due to the cost of enzymes),
- **glycerolysis,** where glycerol is added with the catalyst (slow process),
- **acid catalysis,** where sulphuric acid is used (phosphoric, hydrochloric, organic sulfonic acid can also be used) to catalyse both esterification and transesterification reactions (slower than the alkali-catalysation),
- **acid catalysis followed by alkali catalysis,** where an acid catalyst is used to convert FFAs to methyl esters until FFAs<0.5%, upon which additional methanol and base catalysts are added.

Alkali-catalysed transesterification is the most commercially used method. Sodium hydroxide is widely used in large-scale processing. Other possibilities include sodium methoxide, potassium hydroxide, potassium methoxide, and sodium amide.

Figure 2 gives an overview of the readiness level of the technologies. Considering the feedstock used, technologies can be divided into first generation (1G, that uses "food crops" such as rapeseed, soybeans or palm oil) and second generation (2G, that uses waste vegetable oils, non-edible plants, sludges or animal fat). Biodiesel production from microalgae is still in the early stages of development.

Technology Readiness Levels

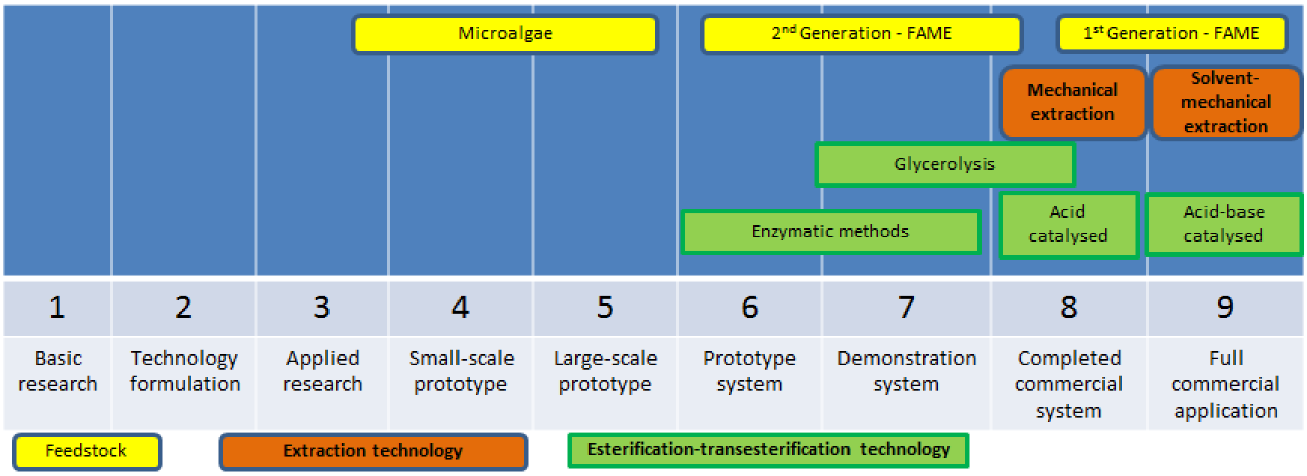


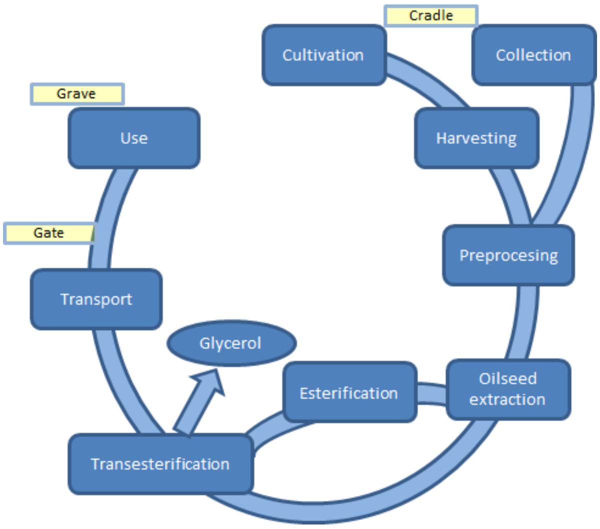
Figure 2. *Technology readiness levels for transesterification of biomass*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Extensively used in industry. **S2**. Cost-efficient process (requires low temperature and pressure) producing 98% yield.	**W1**. The pure plant oil accounts for about 80% of the production cost. **W2**. More costly than fossil diesel.
O1. Alternative non-food feedstocks are on the rise (Jatropha, animal fats, sludge or waste cooking oil). **O2**. Co-products have commercial value. **O3**. Biodiesel tax incentive.	**T1**. Automotive industry not ready for high blends. **T2**. Competition of end uses for feedstock and co-products with other sectors. **T3**. Insufficient information and awareness of society. **T4**. Competition from Hydrotreated Vegetable Oil **T5**. 7% blend limit in the Fuel Quality Directive

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. Cradle to grave (Well to Wheel): includes cultivation (with the production of ancillary products), harvesting or collection (where other biomass crops are used), pre-processing, oilseed extraction (with or without esterification), transesterficication, transport to the fuel tank and use in vehicles.

2. Cradle to gate (Well to Tank): same boundaries as Well to Wheel, excluding the use of the fuel in the vehicle (i.e. Tank to Wheel)

Figure 3. *LCA system boundaries and stages for transesterification of biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for Functional Unit (F.U.) 1 kilometre driven

Raw material input (feedstock)	Rapeseed	Soybean		FFA-rich waste		Microalgae	
LCA boundaries	2	1	2	1	2	1	2
Allocation/substitution	A($-m), S, NA	A($)	A($)	A(m)	A(m)	A(E), S	A($)
Geographical coverage	Spain, Sweden	Argentina-Switzerland		-	-	China	USA
Product	Biodiesel						
References	[5],[10],[11]	[6]	[6]	[4]	[4]	[7], [8]	[9]
Impact categories from Environmental Sustainability Assessment methodology							
Climate change (kg CO_2-eq.)	(4.8E-3 – 0.2)	1.15	1.08	(0.031 – 0.043)	(0.032 – 0.044)	(0.33 – 5.24)	(0.15 – 1)
Ozone depletion (kg CFC-11-eq.)	(4.04E-8 – 3.74E-7)	N.A.	N.A.	(3.71E-9 – 7.53E-9)	(3.84E-9 – 7.77E-9)	N.A.	N.A.
Particulate Matter (kg PM_{10}-eq.)	N.A.	N.A.	N.A.	N.A.	N.A.	(2.73E-4 – 8.36E-3)	N.A.
Photochemical Ozone Formation (kg NMVOC-eq.)	N.A.	N.A.	N.A.	N.A.	N.A.	(6.36E-4 – 1.35E-2)	N.A.
Fresh water eutrophication (kg P-eq.)	(2.41E-5 – 5.99E-4)	1.30E-3	1.01E-3	(3.56E-5 – 4.15E-5)	(1.2E-5 – 1.94E-5)	N.A.	N.A.
Marine water eutrophication (kg N-eq.)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	(1.15E-4 – 5.26E-4)
Resource depletion – water (m^3)	N.A.	N.A.	N.A.	N.A.	N.A.	(1.47E-2-0.15)	(0.12 –0.23)
Resource depletion – mineral (kg Sb-eq.)	(7.82E-4 – 2.27E-2)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Additional impact categories							
Acidification (kg SO_2 eq)	(3.03E-4 – 1.48E-3)	9.10E-3	3.73E-3	(4.91E-4 – 5.82E-4)	(2.11E-4 – 3.01E-4)	2.8E-3	N.A.
Photochemical Ozone Formation (kg C_2H_4-eq.)	(-2.6E-6 – 2.6E-3)	N.A.	N.A.	(3.71E-9 – 7.52E-9)	(3.85E-9 – 7.77E-9)	1.15E-4	N.A.
Fresh water ecotoxicity (1,4-DB-eq.)	N.A.	2.25	2.27	N.A.	N.A.	N.A.	N.A.
Terrestrial ecotoxicity (1,4-DB-eq.)	N.A.	1	1	N.A.	N.A.	N.A.	N.A.
Human toxicity (1,4-DB-eq.)	N.A.	0.36	0.32	N.A.	N.A.	N.A.	N.A.
Nutrient enrichment (kg NO_3)	N.A.	N.A.	N.A.	N.A.	N.A.	3.1E-3	N.A.
Cumulative energy demand (MJ) - non renewable	56.3 – 62.4	9.5	9.13	0.57 – 1.45	0.59 – 1.5	2.09	14.6
Input Energy (MJ)	-0.28 – 0.77	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Land Use competition (m^2 /year)	(0.23 – 0.26)	1.80	1.84	N.A.	N.A.	N.A.	N.A.
Cultivation land use (m^2)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	(3.55E-4 – 7.65E-4)

All values were transformed to the Functional Unit "power to wheels for 1 km driving a midsize car" assuming (when not otherwise specified in the study): Lower Heating Value (LHV) of biodiesel = 37.2 MJ/kg, density = 0.89 kg/l and efficiency of the car = 18.22 km/l [12].

N.A.: Not Available. A: Allocation ($-economic; E-energy; m-mass). S: Substitution.

The normalisation presented in Figure 4 was performed using the normalisation factors provided in the JRC methodology [13] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance:

1 Impact values reported in reference [6] are higher mainly due to the assumption of a lower utilisation efficiency of biodiesel in the car engine (i.e. 0.27kg/km)

2 Reported impact values for microalgae feedstock (references [7], [8] and [9]) are significantly higher in the scenarios that use current commercial data. Future case scenarios present much lower values.

3 Case studies that make allocations based on mass report lower impact values than those based on economic allocations (ref. [5], [11]).

4 Negative impact values (i.e. environmental benefits) are reported for rapeseed biodiesel (reference [11]) when emissions from production and use of glycerine (replacing diesel produced from fossil propane gas) and rapemeal (replacing imported soymeal) are credited to the system.

5 If the emission of biogenic CO_2 is considered as not contributing to Climate Change (references [4], [5]), the estimated climate change impact is significantly lower.

6 In reference [5], the higher impact values reported are mostly due to the intensive agricultural activities required for the rapeseed cultivation.

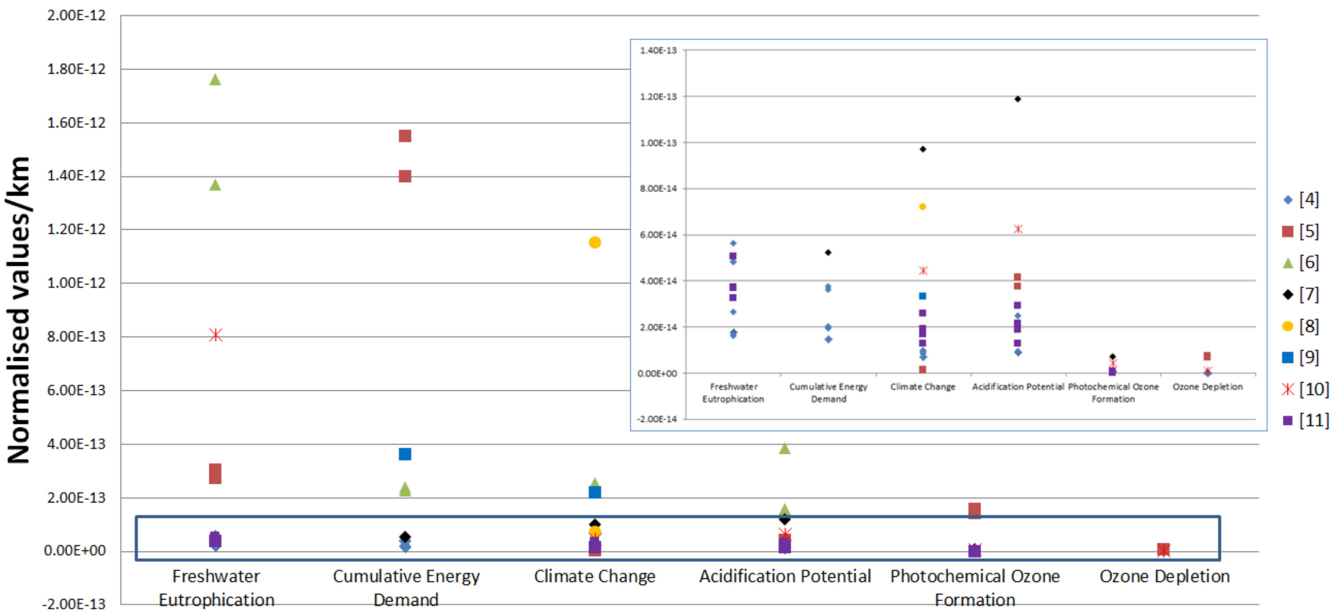


Figure 4. *Environmental performance expressed as normalised impact categories*

REFERENCES / FURTHER INFORMATION

[1] Ma and Hanna, 1999. Bioresource Technol, 70: 1 – 15.
[2] Berrios et al., 2010. Chem Eng J, 160: 473 – 479.
[3] Tasan et al., 2011. Grasas Aceites, 62 (4): 389 – 398.
[4] Dufour and Iribarren, 2012. Renew Energ, 38: 155 – 162.
[5] Gonzalez-Garcia et al., 2013. Int J Life Assess, 18: 61 – 76.
[6] Panichelli et al., 2009. Int J Life Assess, 14: 144 – 159.
[7] Yanfen et al., 2012. Energ Policy, 45: 142 – 151.
[8] Passell et al., 2013. J Environ Manage, 129: 103 – 111.
[9] Brentner et al., 2011. Environ Sci Technol, 45: 7060 – 7067.
[10] Harding et al., 2007. J Clean Prod, 16: 1368 – 1378.
[11] Bernesson et al., 2004. Biomass Bioenerg, 26: 545 – 559.
[12] Quirin et al., 2004. IFEU –CO_2 mitigation – Main Report.
[13] EC – JRC, 2014. Normalisation method and data for environmental footprint – Final version – EUR26842 EN.

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